Sustained spatial attention can affect feature fusion

Ilanit Hochmitz Department of Psychology, University of Haifa, Haifa, Israel

Marc M. Lauffs Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Michael H. Herzog Laboratory of Psychophysics, Brain Mind Institute, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Yaffa Yeshurun Department of Psychology, University of Haifa, Haifa, Israel

When two verniers are presented in rapid succession at the same location, feature fusion occurs. Instead of perceiving two separate verniers, participants typically report perceiving one fused vernier, whose offset is a combination of the two previous verniers, with the later one slightly dominating. Here, we examined the effects of sustained attention—the voluntary component of spatial attention—on feature fusion. One way to manipulate sustained attention is via the degree of certainty regarding the stimulus location. In the attended condition, the stimulus appeared always in the same location, and in the unattended condition it could appear in one of two possible locations. Participants had to report the offset of the fused vernier. Experiments 1 and 2 measured attentional effects on feature fusion with and without eye-tracking. In both experiments, we found a higher rate of reports corresponding to the offset of the second vernier with focused attention than without focused attention, suggesting that attention strengthened the final percept emerging from the fusion operation. In Experiment 3, we manipulated the stimulus duration to encourage a final fused percept that is dominated by either the first or second vernier. We found that attention strengthened the already dominant percept, regardless of whether it corresponded to the offset of the first or second vernier. These results are consistent with an attentional mechanism of signal enhancement at the encoding stage.

Introduction

Spatial covert attention allows us to grant priority in processing of visual information gathered from a specific location without making eye-movements to that location (e.g., Posner, 1980). An extensive amount of evidence suggests that spatial attention has two components: a faster component, attracted to a location by sudden changes in the display—"transient attention"; and a voluntary slower component, controlled by our goals—"sustained attention" (e.g., Cheal & Lyon, 1991; Jonides, 1981; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980; Remington, Johnston, & Yantis, 1992). It has been shown that these two attentional components have different effects on behavior, suggesting separate attentional mechanisms (e.g., Briand, 1998; Hein, Rolke, & Ulrich, 2006; Klein, 1994; Yeshurun & Carrasco, 2008). In this study, we focus on the sustained component of attention and examine its effect on feature fusion.

Feature fusion occurs when two stimuli, which differ in one feature, are presented briefly and in rapid succession at the same retinotopic location. Instead of two separate objects, observers typically report perceiving a single object, whose feature is a combination of the features of the two objects (e.g., Efron, 1967; Efron, 1973; Hermens, Scharnowski, & Herzog, 2009). For example, if a red disk and a green disk are presented in rapid succession, the color of the two disks is fused and a single yellow disk is perceived (e.g., Efron, 1967; Efron, 1973; Yund, Morgan, & Efron, 1983). Similarly, if a vernier stimulus (i.e., two vertical lines separated by a small gap, with a slight horizontal offset) is immediately followed by another vernier stimulus with an offset opposite to the first one (i.e., an antivernier), the offsets of the two stimuli fuse and a single vernier is perceived. Since the offsets of the two

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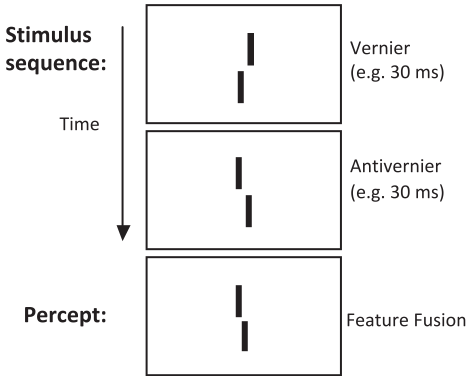

Figure 1. Feature fusion. When a vernier and an antivernier (a vernier with opposite offset direction) are presented in rapid succession, observers do not perceive the individual elements but only one fused vernier with a smaller offset corresponding to the antivernier.

verniers are in opposite directions they partly cancel each other, so that the perceived vernier offset is much smaller (Figure 1). The small perceived offset is in the direction of the second stimulus' offset (e.g., Herzog, Leseman, & Eurich, 2006; Herzog, Parish, Koch, & Fahle, 2003; Scharnowski, Hermens, & Herzog, 2007; Scharnowski, Hermens, Kammer, Ogmen, & Herzog, 2007).

Feature fusion is considered to be a measure of temporal integration, because the features of the two stimuli are integrated across time into a single, coherent, perceptual object. Scharnowski, Hermens, Kammer, et al. (2007) proposed a model that can account for feature fusion. According to this model, feature detector neurons code the offset information (left or right) of the individual verniers. Then, their activation is fed into an integration neuron. Elements presented later influence perception more strongly than earlier ones because the signal of the preceding vernier decays more than that of the trailing antivernier, causing the antivernier to dominate the percept. This model can also account for findings demonstrating that once a sequence of more than one vernier (v) and antivernier (av) is employed, the offset direction of the final percept is highly dependent on the verniers' temporal order and durations. For example, when presenting a v-av-v sequence, increasing the duration of the second vernier in the sequence (i.e., the third stimulus) increased vernier dominance to a larger degree than when the duration of the first vernier was increased, even though the energy of the verniers and antivernier was equal in both cases (e.g., Scharnowski, Hermens, & Herzog, 2007).

Although the model can account for a good deal of the available behavioral data, it can be argued that feature fusion is merely a case of backward masking, in which the antivernier masks the vernier. Yet, with backward masking the visibility of a target is impaired by the mask, whereas with feature fusion one fused vernier is clearly perceived. Critically, with backward masking a more prominent mask generates larger masking effects (i.e., results in poorer target visibility). In contrast, with feature fusion displays, when the single antivernier is replaced by a grating composed of 25 antiverniers (i.e., a considerably stronger "mask"), the vernier dominates the final perception (i.e., it becomes more visible; e.g., Herzog, Fahle, & Koch, 2001; Herzog & Koch, 2001; Hermens et al., 2009; Hermens, Scharnowski, & Herzog, 2010). These results suggest that feature fusion is not a simple case of backward masking.

The current study examined the effect of spatial sustained attention on feature fusion. Feature fusion is considered to occur at an early stage of visual information processing (Hermens et al., 2009; Hermens et al., 2010). Research on the effects of spatial attention on early visual processing provides some reasons to suppose that feature fusion might be affected by spatial attention. It is well established that attention improves early aspects of visual perception such as contrast sensitivity (e.g., Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Dosher & Lu, 2000; Huang & Dobkins, 2005; Lu & Dosher, 1998; Lu & Dosher, 2000; Smith, Wolfgang, & Sinclair, 2004; Solomon, 2004) and spatial resolution (e.g., Carrasco, Williams, & Yeshurun, 2002; Golla, Ignashchenkova, Haarmeier, & Their, 2004; Yeshurun & Carrasco, 1998; Yeshurun & Carrasco, 1999). For instance, regarding spatial resolution, it has been found that the advance allocation of spatial attention improves performance in acuity tasks such as the detection of a small spatial gap with "Landolt-squares" (e.g., Carrasco et al., 2002; Golla et al., 2004; Yeshurun & Carrasco, 1999), as well as hyperacuity tasks like discrimination of offset-direction with vernier targets (e.g., Yeshurun & Carrasco, 1999). In addition, directing attention to the target location of a texture target enhanced the ability to segment it from the texture background when this target appeared in the periphery where the spatial resolution was too low for the scale of the texture, but impaired performance at more central locations where the spatial resolution was too high (Yeshurun & Carrasco, 1998; Yeshurun & Carrasco, 2000).

Spatial attention has also been found to affect temporal aspects of visual processing. For instance, it has been found that transient spatial attention degrades temporal resolution—the ability to resolve rapid luminance changes in time. Using the two-flash fusion paradigm, several studies demonstrated that observers' ability to detect a brief temporal gap occurring between two successive light flashes was reduced when observers allocated their attention in advance to the flashes' location (e.g., Rolke, Dinkelbach, Hein, & Ulrich, 2008; Yeshurun, 2004; Yeshurun & Levy, 2003). Similarly, Hein, Rolke, and Ulrich (2006) demonstrated that involuntary attention impairs temporal order discrimination of two spatially adjacent dots, whereas voluntary attention enhances it. Attentional effects were also found for the opposing temporal process. Visser and Enns (2001) examined the effects of attention on temporal integration, using the attentional blink paradigm. In this paradigm participants are presented with two targets, separated by a temporal lag typically ranging from 100 to 700 ms. When participants are asked to identify the two targets, they usually demonstrate near perfect identification of the first target, whereas the identification of the second target varies as a function of the lag. Second target identification rates are poor at short lags, and they increase as lag duration increases (e.g., Raymond, Shapiro, & Arnell, 1992). It is suggested that the failure in the identification of the second target for short lags can be attributed to impoverished attention resources due to the processing of the first target (e.g., Shapiro, Arnell, & Raymond, 1997). To measure temporal integration, Visser and Enns used as the second target a 5×5 dots matrix of which one dot was missing. The task was to localize the missing dot. Critically, the dot matrix was divided into two consecutive frames, each composed of 12 dots (25 dots minus the missing dot). Hence, dot localization required integrating the two frames across time. Temporal integration was manipulated by varying the interstimulus interval (ISI) between frames. As expected, missing dot localization improved with shorter ISIs that allows the two matrix frames to integrate across time. However, this performance enhancement was less evident when the matrix frames appeared within the time window of the attentional blink (i.e., when the matrix was presented in close temporal proximity to the first target). This finding suggests that under limited attentional resources temporal integration is shortened (Visser & Enns, 2001).

Given these demonstrations of attentional effects on early visual processing, it is reasonable to assume that spatial attention will also affect feature fusion. In the current study we tested this hypothesis. So far feature fusion was only examined in the fovea. However, in order to manipulate spatial attention, the visual display should involve spatial uncertainty. To achieve that uncertainty, we presented the feature fusion display in the periphery, and manipulated spatial sustained attention by varying the degree of uncertainty regarding the stimuli location. The attended condition was a full certainty condition, in which the stimuli—a vernier followed by an antivernier—appeared at the same peripheral location throughout the block. This allowed the observers to allocate spatial attention in advance to the stimuli location. In the unattended condition, spatial uncertainty was introduced: The stimuli could equally likely appear in one of two possible peripheral locations (to the right or left of fixation). Hence, in this condition the observers could not allocate attention to the stimuli location in advance. Experiments 1 and 2 examined whether spatial sustained attention affects feature fusion with and without measuring eye-movements. Experiment 3 explored the mechanism underlying the observed attentional effect. In all three experiments, the observers had to report their perceived offset direction, and we measured how often observers reported an offset that matches that of the first stimulus (the vernier offset). If the vernier offset report rate was above 50% it indicated that the vernier dominated the final percept (vernier dominance), and if it was below 50% it indicated that the antivernier (the second stimulus) dominated perception (antivernier dominance). If the vernier offset report was around 50%, it indicated that the vernier and the antivernier had a similar contribution to the final percept (Hermens et al., 2009). Here, we examined the effect of attention on feature fusion by comparing the reported vernier offset direction in the attended and unattended condition. If attention can affect feature fusion, the degree of vernier/antivernier dominance will be different in the two attentional conditions.

Experiment 1

Experiment 1 was designed to examine whether spatial sustained attention can affect feature fusion. To that end, we measured the extent to which feature fusion occurs with and without focused sustained attention. Feature fusion was produced using a vernier and an antivernier, presented one after the other in the same location with no intermediate time interval. In the attended condition, the stimulus sequence appeared at the same peripheral location throughout the block. The participants were informed of this location before the beginning of the block, which enabled them to attend this location in advance. In the unattended condition, the stimuli could appear in one of two possible locations, producing spatial uncertainty, which prevented the advance allocation of attention to the stimuli location.

Method

Participants

Eight students from the University of Haifa participated in this experiment. Participants were naive to the purpose of the study, and had normal or corrected-to-normal vision. The visual acuity of all participants was tested using the Freiburg visual acuity test (Bach, 1996). Observers had to score at least 1.0 on this test (corresponding to 20/20) in order to participate. This study adhered to the Declaration of Helsinki.

Stimuli and apparatus

The stimuli were presented on a 21-in. CRT monitor of a PowerMac G4 computer (1,024 × 768 resolution at refresh rate of 120 Hz), using MATLAB (MathWorks, Natick, MA) and the Psychophysics Toolbox extensions (Brainard, 1997). A dim background light illuminated the room. The stimuli were composed of a sequence of a white vernier and antivernier presented on a black background. The vernier consisted of two vertical lines, each measuring 10′ (arc minutes) in height. The two lines were separated by a 1′ vertical gap, and were slightly offset horizontally (randomly to the right or left with equal probability). The antivernier had the same spatial parameters as the vernier, except that its offset was in the opposite direction of the vernier (Figure 1). If the vernier was offset to the left, the antivernier was offset to the right and vice versa.

The horizontal offset was adjusted for each participant, in a preliminary session consisting of six blocks of 84 trials per each block. In this session, the participants performed the experimental task with several offset sizes, and the vernier-antivernier sequence always appeared to the right of fixation. The chosen offset had to meet two criteria: (a) It had to yield around 30% vernier dominance (i.e., the vernier offset direction was reported in 30% of the trials); and (b) participants had to perceive only one fused vernier with no apparent motion percept. This was based on the finding that with large offset sizes some participants reported seeing the upper and lower segments move in opposite directions (Scharnowski, Hermens, Kammer, et al., 2007). The chosen horizontal offsets ranged from 60″ to 120″ ($Mode = 120''$). In the experimental session there were two attentional conditions. In the attended condition, the vernier-antivernier sequence was always presented to the right of fixation at 2° of eccentricity. In the unattended condition, the stimuli could appear either to the right or to the left of fixation, with equal probability, at 2° of eccentricity.

Procedure

The participants viewed the stimuli from a distance of 2 m, and were asked to fix their gaze on a central fixation cross throughout the trial. Each trial began with a fixation cross (750 ms), followed by the vernier-antivernier sequence, each presented for 30 ms with no ISI. The offset direction of the vernier was equally often to the right or to the left, presented in a random order. Each attentional condition was tested in three separate blocks, each consisting of 80 trials. The order of the blocks was randomized across participants, and the participants knew in advance which block they were about to perform (one vs. two possible locations). The participants' task was to indicate the perceived offset direction (i.e., whether the upper line of the vernier was to the left or to the right of the lower line).

Before the experimental session, each participant performed a short practice session comprised of 20 trials per attentional condition.

Results and discussion

Our main dependent measure was the percentage of trials in which the observers reported the offset direction of the first stimulus (the vernier). A vernier offset report above 50% indicated vernier dominance, and a vernier offset report below 50% indicated antivernier dominance. Overall, in both conditions, the percentage of trials in which the observers reported the vernier offset was lower than 50% (Figure 2).

Thus, the results of this experiment replicate those of previous studies demonstrating that under such presentation conditions the offset of the antivernier dominates perception (e.g., Herzog et al., 2003; Herzog et al., 2006; Scharnowski, Hermens, Kammer, et al., 2007). Most important for the goal of the current study, antivernier dominance differed in the two attentional conditions. Specifically, antivernier dominance was higher in the attended condition than in the unattended condition. A one-way repeated-measures ANOVA, performed on the vernier offset report rate, indicated that this effect was highly significant: $F(1, 7) = 42.76$, $p < 0.0004$, $\eta_p^2 = 0.86$. Moreover, this pattern of results was consistent for all participants. Figure 3 illustrates the data points of all the participants for the two attentional conditions. As can be seen in the figure, all data points fall below the equality diagonal, reflecting the fact that for all participants vernier dominance was higher in the unattended condition compared with the attended condition. These findings suggest that sustained spatial attention affects feature fusion. However, in the attended condition of this experiment, the stimuli location was constant throughout the block. Although participants were asked to maintain fixation, we cannot rule out the possibility that they, at least on some trials, moved their eyes to foveate the stimuli. In this case, the effect found in this experiment might be, at least partially, due to eye-movements.

Experiment 2

In order to eliminate eye-movements as an alternative explanation of the results of Experiment 1, we

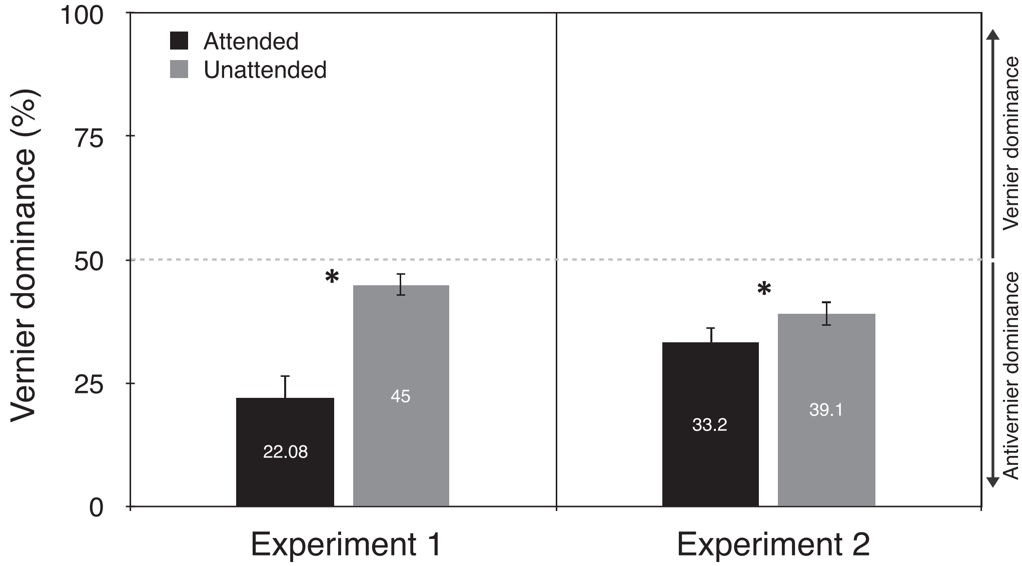

Figure 2. Vernier dominance (percentage of vernier offset report) as a function of the attentional conditions in Experiments 1 and 2. Error bars correspond to one within-subject standard error of the mean (calculated using the methods described in Cousineau, 2005).

conducted a second experiment in which we tracked the observers' eye-movements. If spatial covert attention indeed affects feature fusion, we should get similar results in Experiment 2 to those of Experiment 1 even though eye-movements were precluded.

Method

Participants

Ten students from the École Polytechnique Fédérale de Lausanne (EPFL) participated in this experiment; all were naive to the purpose of the study, and had normal or corrected-to-normal vision. The visual acuity of all participants was tested using of the Freiburg visual acuity test (Bach, 1996). Observers had to score at least 1.0 on this test (corresponding to 20/20) in order to participate. This study adhered to the Declaration of Helsinki.

Stimuli, apparatus, and procedure

Stimuli were presented on a standard 24-in. LCD Asus VG248QE computer screen (1,920 × 1,080 resolution at refresh rate 120 Hz). Eye-movements were recorded using an SMI iViewX Hi-Speed 1250 Eye-tracker. Data were recorded binocularly at 500 Hz but immediately averaged over both eyes to reduce noise.

The stimuli and procedure were similar to that of Experiment 1 except for the following: Offset sizes were again adjusted per each observer, this time by using a PEST staircase procedure, such that the determined

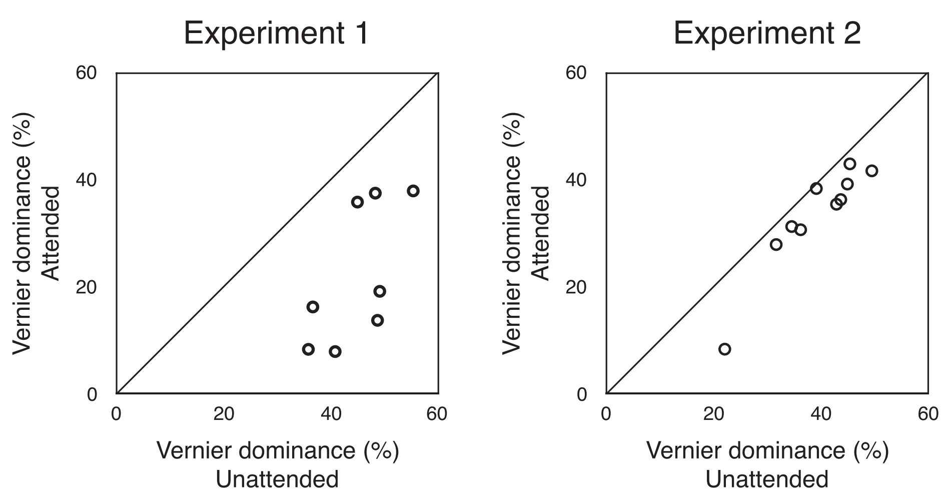

Figure 3. Vernier dominance (%) in the attended condition as a function of vernier dominance in the unattended condition for each participant of Experiments 1 and 2.

offset yielded 25% vernier dominance. The staircase procedure was conducted in the same session but in a separate block. This block consisted of 80 trials identical to the experimental trials in the attended condition. The adjusted offset sizes ranged from 18″ to 98″ ($Mode = 35''$). Also, stimuli were only presented after a fixation on the central fixation cross was detected.

Results and discussion

Similar to Experiment 1, the overall percentage of trials in which the observers reported the vernier offset was lower than 50% in both conditions. Critically, once again, antivernier dominance was higher when participants could allocate their attention in advance to the stimuli location (Figure 2). A one-way repeated-measures ANOVA, performed on the vernier offset report rate, indicated that this effect was also significant: $F(1, 9) = 26.21$, $p < 0.0007$, $\eta_p^2 = 0.74$. Also, similar to Experiment 1, this pattern of results was present for most of the participants (Figure 3).

The fact that the effect of attention on feature fusion was not eliminated when eye-movements were precluded suggests that the effect observed in Experiment 1 was not merely due to eye-movements; rather, it is indeed due to the allocation of covert attention to the stimuli location. However, as can be seen in Figure 2, the effect in Experiment 2 was smaller. A pooled t test performed on the vernier dominance differences between the attended and unattended conditions across the two experiments confirmed that this difference is significant, $t(16) = 5.059$, $p < 0.0002$, Cohen's $d = 2.39$ (reflected reflected also in the difference in effect sizes). This difference in the effect of attention between the two experiments will be discussed in more detail in the General discussion section.

Overall, the results of Experiments 1 and 2 demonstrate that sustained spatial attention affects feature fusion. Specifically, in both experiments, the antivernier offset dominated the final percept, with both attentional conditions. However, with focused attention the antivernier dominance was stronger, suggesting that the final percept of a single fused stimulus might have been clearer with than without focused attention. Moreover, the fact that the effect of attention on feature fusion was found even when eye-movements were precluded (i.e., Experiment 2) suggests that the effect observed in Experiment 1 was not merely due to eye-movements; rather, it is indeed due to the allocation of covert attention to the stimuli location.

Because feature fusion is considered to occur at a relatively early stage of visual processing, these results are consistent with previous studies demonstrating the effect of spatial attention on early or basic aspects of visual processing, such as contrast sensitivity and spatial resolution (reviewed in Carrasco & Yeshurun, 2009). Yet, the nature of this attentional effect remains unclear. Experiment 3 aimed to provide a better understanding of the attentional mechanism responsible for feature fusion enhancement.

Experiment 3

Experiments 1 and 2 showed that antivernier dominance, which typically serves as a marker for feature fusion, increased when participants allocated attention in advance to the stimuli location. This finding suggests that sustained spatial attention can affect feature fusion. In the current experiment we examined the mechanism underlying this effect of attention on feature fusion. One possible explanation of this finding is that attention improves the quality of the representation of each of the stimuli in the sequence and therefore results in a better representation of the fused percept. One mechanism by which attention might exert this kind of effect is signal enhancement. According to the signal enhancement hypothesis, attention improves stimulus encoding at the attended location (e.g., Bashinski & Bacharach, 1980; Yeshurun & Carrasco, 1998; Downing, 1988; Lu & Dosher, 1998; Posner, 1980). In this experiment we tested the hypothesis that attention affects feature fusion by enhancing the representation of the final percept. We took advantage of the fact that the final percept of the fusion stimuli can be modified by manipulating the duration of the stimuli. Specifically, if the duration of the first stimulus in the sequence (the vernier) is longer than the duration of the second stimulus (the antivernier), its offset dominates the final fused percept (vernier dominance). In contrast, if the duration of both stimuli is equal, as was the case in Experiments 1 and 2, the offset of the second stimulus, the antivernier, dominates perception (e.g., Scharnowski, Hermens, & Herzog, 2007). Hence, if attending to the sequence location results in improved representation of the fused percept, this percept should be enhanced regardless of its direction (i.e., regardless of whether it reflects vernier dominance or antivernier dominance).

To test this hypothesis we included in this experiment the same attention conditions, but also two "dominance" conditions: 25% and 75% vernier dominance. The 25% dominance condition was identical to Experiment 2. That is, the duration of the two stimuli in the sequence was equal, and the staircase procedure was designed to yield 25% vernier dominance. In the 75% dominance condition the vernier was presented twice as long as the antivernier, and the staircase procedure was designed to yield 75% vernier dominance. Finally, for comparison, we also added a "single vernier" condition in which only the vernier was presented (i.e., fusion was not involved).

If sustained attention affects feature fusion through signal enhancement, then it should strengthen the already dominant percept. That is, in the 25% condition we expected to replicate the results of Experiments 1 and 2: Antivernier dominance should be higher in the attended condition compared to the unattended condition. In the 75% condition, the more prominent percept is a fused vernier with an offset direction corresponding to that of the first vernier; therefore, in this condition, we expected to find higher vernier dominance in the attended than in the unattended condition. As for the single vernier condition, Yeshurun and Carrasco (1999) previously found that spatial transient attention enhances vernier offset discrimination. This result was interpreted in terms of signal enhancement. However, whereas that study employed transient attention manipulated via peripheral cues, our study focused on the sustained component of spatial attention. It has been previously argued that transient and sustained attention operate at different stages within the visual system, which may account for the fact that sometimes they show differential effects on performance (e.g., Briand, 1998; Chica, Bartolomeoa, & Lupiánez, 2013; Hein et al., 2006; Klein, 1994; Yeshurun & Carrasco, 2008). Thus, the effect of transient attention on vernier offset discrimination may or may not be replicated with sustained attention. If *sustained* spatial attention can also affect vernier offset discrimination via signal enhancement, we expected to replicate the results of Yeshurun and Carrasco (1999). In addition, because the single vernier condition does not involve fusion, it also allows us to test whether sustained attention affects feature fusion in a unique manner, which is different from its effect on a single vernier offset discrimination.

Method

Participants

Eleven students from the École Polytechnique Fédérale de Lausanne (EPFL) participated in this experiment; all were naive to the purpose of the study and had normal or corrected-to-normal vision. Their visual acuity was assessed as in Experiment 2.

Stimuli, apparatus, and procedure

The stimuli, apparatus and procedure were identical to those of Experiment 2 except for the following: Two vernier dominance conditions were used, 25% and 75%. The 25% condition was identical to that of Experiment 2. Both stimuli were presented for 30 ms, and the staircase procedure performed before the experimental session was set to generate a final offset that yields 25% vernier dominance. In the 75% condition the vernier was presented for 30 ms and the antivernier was presented for 15 ms. Additionally, the staircase procedure was set to generate a final offset that yields 75% vernier dominance. In the single vernier condition, a single vernier stimulus was presented for 30 ms, with an offset identical to that used in the 25% condition. Chosen offset sizes ranged from 50″ to 60″ (*Mode* = 60″) in the 25% condition, and from 55″ to 120″ (*Mode* = 55″) in the 75% condition.

Each dominance condition was run for four blocks of 80 trials, two blocks per attentional condition. The single vernier blocks were always run at the end of the session (i.e., after the 25% and 75% conditions). Whether the 75% or the 25% condition was run first was counterbalanced across participants.

Results and discussion

A two-way repeated-measures ANOVA, with the factors dominance (25%, 75%, single) and attention (attended, unattended), was conducted on the vernier offset report rate. As expected given previous studies who used a duration manipulation (e.g., Scharnowski, Hermens, & Herzog, 2007), there was a significant main effect for the dominance condition: $F(2, 10) = 49.41$, $p < 0.0001$, $\eta_p^2 = 0.83$ (Figure 4); in the 25% condition the antivernier dominated the percept, whereas the vernier dominated in the 75% and single conditions (Figure 4). There was no main effect of attention, but the interaction was highly significant: $F(2, 10) = 39.89$, $p < 0.0001$, $\eta_p^2 = 0.80$. *t* tests indicated that the effect of attention in all three dominance conditions was significant, but in opposite directions: In the 25% condition, vernier offset report was lower in the attended than unattended condition, $t(10) = -5.95$, $p < 0.0001$, Cohen's $d = -1.79$, or in other words, antivernier dominance was higher in the attended than the unattended condition. This finding replicates the results of Experiments 1 and 2. In contrast, in the 75% condition, the vernier offset report rate was significantly higher in the attended than in the unattended condition, $t(10) = 5.94$, $p < 0.0001$, Cohen's $d = 1.79$, or in other words, vernier dominance was higher in the attended than unattended condition. Finally, in the single vernier condition, the vernier offset report rate was also significantly higher in the attended than in the unattended condition, $t(10) = 4.073$, $p < 0.002$, Cohen's $d = 1.23$, confirming that sustained attention improves vernier offset discrimination. Importantly, in each of the dominance condition, the pattern of results was consistent for most of the participants. As can be seen

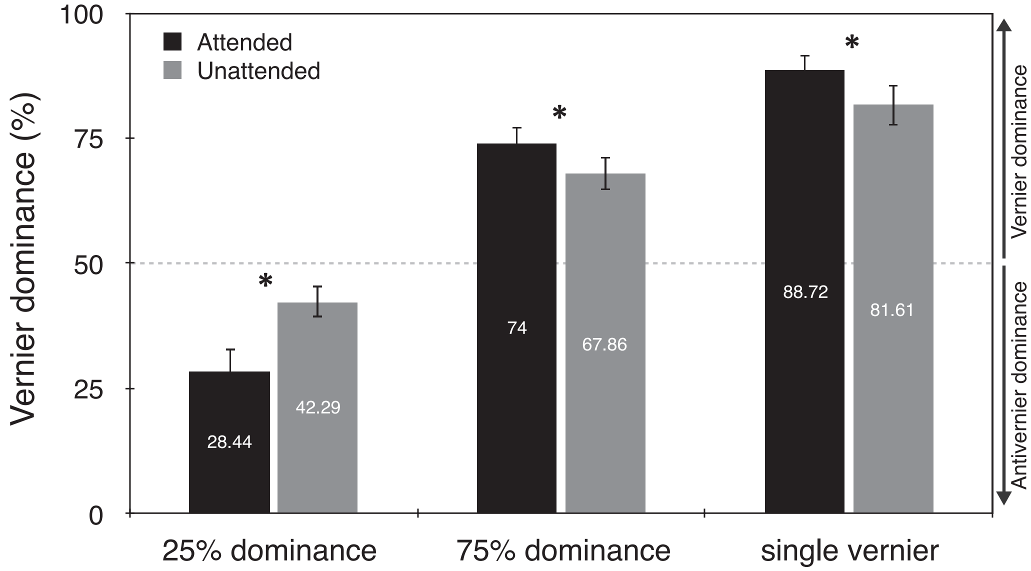

Figure 4. Vernier dominance (percentage of trials in which the reported offset is in line with the first vernier) as a function of attentional and dominance conditions. Error bars correspond to one within-subject standard error of the mean (calculated using the methods described in Cousineau, 2005).

in Figure 5, in the 25% dominance condition, most of the data points fall below the equality diagonal, whereas in the 75% condition and the single vernier condition, most of the data points fall above the equality diagonal. Thus, for the majority of the participants, in the 25% dominance condition, vernier dominance was higher in the unattended condition versus the attended condition, whereas in the 75% and the single vernier conditions most of the participants demonstrated the reversed pattern. Thus, as predicted by the signal enhancement hypothesis, allocating sustained attention to the stimulus location strengthened the final fused percept that was dominant under divided diffused attention.

Interestingly, as can be seen in Figure 4, the effect of attention (i.e., the difference between attended and unattended conditions) in the 25% condition ($M =$ 13.85) is about twice as large as the attentional effect in the 75% or single vernier conditions ($M = 6.14$ and $M =$ 7.11, respectively). To test whether this difference is reliable statistically, we performed a one-way repeated-measures ANOVA on this difference between the attentional conditions, with dominance (25%, 75%, single) as the within-subject factor. This analysis revealed a significant effect of dominance: $F(2, 10) =$ 7.28, $p < 0.005$, $\eta_p^2 = 0.42$. Additional t tests indicated that the difference between the attentional conditions was significantly larger in the 25% than the 75% dominance condition and single-vernier condition, $t(10) = 3.84$, $p < 0.002$, Cohen's $d = 1.16$; $t(10) = 2.44$, $p < 0.02$, Cohen's $d = 0.74$, respectively, but there was no significant difference between the 75% and single

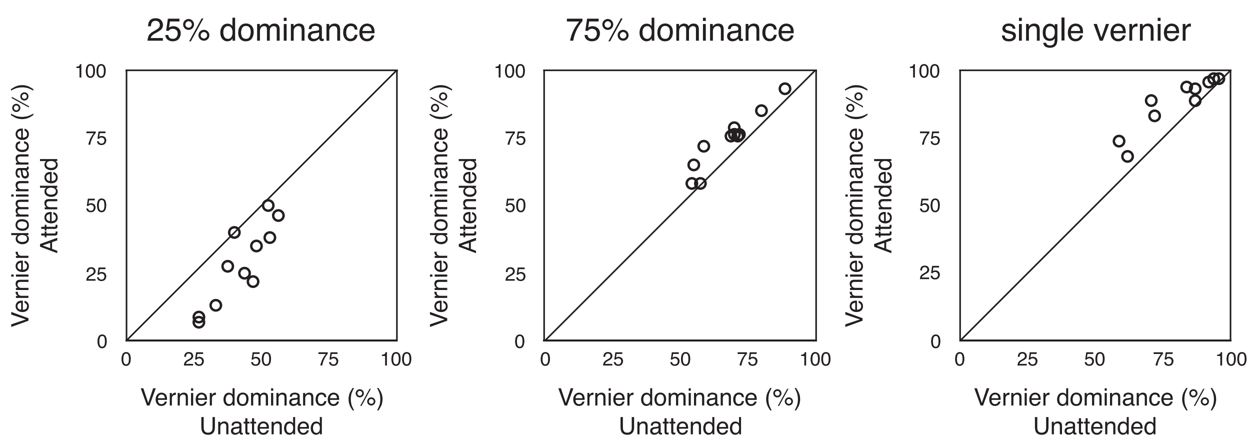

Figure 5. Vernier dominance (%) in the attended condition as a function of vernier dominance in the unattended condition for each participant of Experiment 3.

vernier condition ($p = 0.288$). These various effects of attention allocation and dominance manipulations are discussed in detail in the General discussion section.

Note that because the stimuli in the attended condition always appeared at the same position whereas in the unattended condition it could appear in one of two possible positions, the rate of position repetition was higher in the attended than in the unattended condition. Hence, the difference in vernier dominance between these attentional conditions may be merely due to the difference in position repetition, rather than to whether or not attention was focused on the stimulus location. Indeed, it was demonstrated in the past that position repetition can facilitate performance (e.g., Kristjansson, Vuilleumier, Malhotra, Husain, & Driver, 2005; Maljkovic & Nakayama, 1996). To test this alternative explanation, we once again compared vernier dominance in the attended and unattended conditions; but this time, for the unattended condition, we only included trials in which the stimuli position was repeated. Hence, for both the attended and unattended conditions, the analysis only included trials in which the stimulus location was the same as in the previous trial. The number of repetition trials included in the analysis for the unattended condition varied across participants due to randomization, and it ranged from 63 to 80 trials per subject ($M = 72$). If the observed difference in vernier dominance between the attended and unattended conditions was merely due to repetition, there should be no significant difference when only repetition trials are included. However, just as in our analysis of the full data set, a paired t test revealed a significant difference in vernier dominance between the attentional conditions with all three dominance conditions [25% condition: $t(10) = -6.199$, $p < 0.001$, Cohen's $d = -1.87$; 75% condition: $t(10) = 4.567$, $p < 0.001$, Cohen's $d = 1.38$; single vernier: $t(10) = 3.367$, $p < 0.007$, Cohen's $d = 1.02$]. Moreover, when we compared the unattended repetition trials with unattended nonrepetition trials (i.e., trials in which the position of the stimuli in the current trial was different than that in the previous trial), no significant difference was found ($p > 0.3$ for all three dominance conditions). Thus, the effect of attention on feature fusion goes beyond mere position repetition.

General discussion

This study examined the effects of covert sustained attention on feature fusion. Experiments 1 and 2 measured the effect of attention on feature fusion with and without controlling for eye-movements. Experiment 3 examined whether the attentional effects found in Experiments 1 and 2 can be attributed to a signal enhancement mechanism. In all three experiments feature fusion was produced by presenting a sequence of vernier and antivernier stimuli, presented one after the other to the same location with no intervening temporal interval. Spatial sustained attention was manipulated by varying the degree of spatial uncertainty: In the attended condition the location of the stimulus sequence was fixed for the entire block, allowing attention allocation in advance to this location; in the unattended condition the location of the sequence varied randomly between two possible locations and therefore did not allow advance attention allocation to the upcoming stimulus location.

Attentional effects on feature fusion were found in all three experiments. In Experiments 1 and 2 we found a greater degree of antivernier dominance when participants could allocate attention in advance to the sequence location, and in Experiment 3 attention increased whatever dominance was already apparent in the unattended condition. These findings are the first demonstration that sustained spatial attention can affect the outcome of temporally fused stimuli, and they are in line with a considerable number of studies demonstrating the effects of *covert* attention on early visual processing (e.g., Carrasco et al., 2002; Carrasco, Ling, & Read, 2004; Ling & Carrasco, 2006; Pestilli, Viera & Carrasco, 2007; Golla et al., 2004; Yeshurun & Carrasco, 1998; Yeshurun & Carrasco, 1999). Different attentional mechanisms might account for the observed attentional modulation of feature fusion. One such attentional mechanism operates on decisional processes via modulation of the decision criteria the observers are adopting, or the decisional weights that are assigned to information gathered at the attended and unattended locations (e.g., Kinchla, 1980; Kinchla, Chen, & Evert, 1995; Palmer, 1994; Shaw, 1984). This mechanism, however, cannot account for our current findings because it is only relevant when the attentional manipulation conveys useful information regarding the likelihood of the different possible behavioral responses (e.g., when one response is more likely in the attended than unattended condition). In all three experiments of this study the task was a two-alternative forced choice task, which included two equally likely responses regardless of the attentional manipulation, and hence it did not afford attentional effects on decision processes.

Another possible attentional mechanism operates through external or internal noise reduction (e.g., Dosher & Lu, 2000; Graham, Kramer & Haber, 1985; LaBerge, 1995; Lu & Dosher, 1998; Shiu & Pashler, 1994; Shiu & Pashler, 1995; Sperling & Dosher, 1986). The idea is that the advance allocation of spatial attention to the relevant location allows observers to monitor only this location instead of monitoring all possible locations, thereby reducing the number of locations that needed to be monitored and accordingly the statistical noise introduced at these locations by irrelevant stimuli or internal noise. However, as with the previous attentional account, this noise-reduction mechanism cannot account for our findings. This is because in all three experiments of this study the task relevant stimuli (the vernier and antivernier) were suprathreshold and presented alone, without additional task-irrelevant items. When suprathreshold stimuli are employed, the internal noise generated at the other empty locations becomes negligible, and if there are no irrelevant items in the visual display, there is also no external noise. Thus, given the displays employed in this study, there was neither internal nor external noise to reduce, and therefore attentional noise reduction does not appear to be involved in the attentional effects found here.

Ruling out these two possible mechanisms leaves us with a third attentional mechanism—signal enhancement (e.g., Bashinski & Bacharach, 1980; Yeshurun & Carrasco, 1998; Downing, 1988; Lu & Dosher, 1998; Posner, 1980). The hypothesis here is that allocating attention to the relevant location enhances the quality of the sensory representation at the attended location, and evidence in support of this hypothesis was gathered in both behavioral studies (e.g., Bashinski & Bacharach, 1980; Downing, 1988; Lu & Dosher, 1998; Yeshurun & Carrasco, 1998; Yeshurun & Carrasco, 1999) as well as neurophysiological studies (e.g., Brefczynski & DeYoe, 1999; Desimone & Ungerleider, 1989; Desimone, Wessinger, Thomas & Schneider, 1990; Martinez et al., 1999; Moran & Desimone, 1985; Motter, 1993; Spitzer, Desimone & Moran, 1988). For instance, single-cell recordings have demonstrated attentional modulations in neural responding of V1 and V4 cells (e.g., McAdams & Maunsell, 1999; Motter, 1993); neurons' responses to attended stimuli were stronger and more selective in both V4 (McAdams & Maunsell, 1999; Spitzer et al., 1988) and MT/MST (e.g., Treue & Maunsell, 1996). Similarly, fMRI studies have shown attentional facilitation in both striate and extrastriate visual cortex (e.g., Brefczynski & DeYoe, 1999; Martinez et al., 1999). This hypothesis gains direct support in our study, particularly in Experiment 3. If attending the location at which the vernier and antivernier appear improves the sensory encoding of both stimuli, then the final, fused percept should also be strengthened, regardless of whether this final percept reflects vernier or antivernier dominance. Following this prediction, when the fused percept in the unattended condition was dominated by the antivernier offset (Experiments 1, 2, and 3: 25% condition), attending the stimulus location resulted in an even stronger antivernier dominance. Likewise, when the fused percept in the unattended condition was dominated by the vernier offset (Experiment 3: 75% condition), attending the sequence location resulted in an even stronger vernier dominance. These findings suggest that spatial sustained attention affects feature fusion via signal enhancement.

Also in line with the signal enhancement hypothesis is the finding that in the single vernier condition of Experiment 3, in which only a single stimulus was presented, vernier offset discrimination was better in the attended than unattended condition. This is consistent with Yeshurun and Carrasco's (1999) finding that directing transient spatial attention via peripheral cues to the vernier location improves vernier offset discrimination, and it suggests that sustained attention, like transient attention, can increase hyperacuity.

As mentioned above, Experiment 3 revealed another interesting finding. The effect of attention on feature fusion was more pronounced in the 25% dominance condition than in the 75% and single vernier conditions. In fact, the effect size was almost twice as large in the 25% condition. This result might be due to an involvement of transient attention in addition to that of sustained attention. Transient attention operates in a stimulus-driven manner, and it is typically triggered by an abrupt onset or other rapid changes in the visual display. It is a fast form of attention with beneficial effects evident as early as 50 ms from the appearance of its trigger, though optimal effects require ~100 ms (e.g., Cheal & Lyon, 1991; Jonides, 1981; Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980; Remington, Johnston, & Yantis, 1992). It is possible, therefore, that the presentation of the first stimulus in our sequence—the vernier—attracted transient attention to its location. Indeed, it has been suggested that when a stream of stimuli is presented to the same location, like in a rapid serial visual presentation paradigm (RSVP), transient attention is triggered by the first stimulus and may assist the identification of the following stimulus (e.g., Bowman & Wyble, 2007). Although transient attention is attracted to the relevant location already by the onset of the first stimulus, the process of deploying attention takes time, and the second stimulus may disproportionally benefit from the deployment of transient attention (e.g., Bowman & Wyble, 2007; Wyble, Bowman, & Potter, 2009). Thus, due to the time required to deploy transient attention, if transient attention was indeed attracted to the sequence location by the onset of the vernier, the second stimulus in our sequence—the antivernier—might have been the one to benefit from the additional enhancement brought about by transient attention. Moreover, given the particularly brief presentation of each stimulus in the sequence, and given the time required for the deployment of transient attention, this additional "boost" of the second stimulus could only happen in the attended condition in which attention was already allocated to the sequence location allowing a faster deployment of transient attention. It is also probable that this disproportionate benefit in favor of the antivernier only took place in the 25% condition, since in the 75% condition the antivernier duration was halved, leaving little room for transient attention to generate any effect, and the same logic holds for the single vernier condition. Taken together, we suggest that whereas in the 25% condition the antivernier processing was further facilitated by transient attention, in the 75% and single vernier conditions any attentional gain was restricted to sustained attention operating on both the vernier and antivernier representation.

Finally, another interesting finding that emerged in this study is that the effect of the spatial certainty manipulation was considerably smaller in Experiment 2 in comparison to Experiment 1. Because the exclusion of eye-movements in Experiment 2 was the main difference between the two experiments, it is possible that the larger effect found in Experiment 1 was due to the fact that in the attended condition of this experiment, the participants could move their eyes to foveate the stimuli. If so, this would suggest that fusion is more prevalent in the fovea than in the periphery, which in turn would strengthen the claim that feature fusion reflects temporal integration. This is because in comparison to foveal processing, the processing in the periphery exhibits shorter temporal integration (e.g., Swanson, Pan, & Lee, 2008). That said, the difference between the two experiments may also be due to other factors that seem less meaningful, but may nevertheless mediate the difference (e.g., the experiments were conducted in different labs). Hence, further research is required to establish whether or not feature fusion is less prevalent in the periphery.

To conclude, this study is the first to examine the effects of spatial sustained attention on feature fusion, and it demonstrates that directing covert attention to the stimuli location affects feature fusion via signal enhancement. Specifically, we have found that attention strengthened the already dominating final fused percept, most likely by enhancing the representation of each of the fused stimuli.

Keywords: feature-fusion, sustained attention, signal enhancement

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Corresponding author: Ilanit Hochmitz.
Email: ilanit57@gmail.com.
Address: Department of Psychology, University of Haifa, Haifa, Israel.

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