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ScienceDirect

Vision Research 47 (2007) 166–178

Vision Research

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Attention makes moving objects be perceived to move faster

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Received 24 February 2006; received in revised form 29 September 2006

Abstract

Although it is well established that attention affects visual performance in many ways, by using a novel paradigm [Carrasco, M., Ling, S., & Read. S. (2004). Attention alters appearance. *Nature Neuroscience, 7*, 308–313.] it has recently been shown that attention can alter the perception of different properties of stationary stimuli (e.g., contrast, spatial frequency, gap size). However, it is not clear whether attention can also change the phenomenological appearance of moving stimuli, as to date psychophysical and neuro-imaging studies have specifically shown that attention affects the adaptability of the visual motion system. Here, in five experiments we demonstrated that attention effectively alters the perceived speed of moving stimuli, so that attended stimuli were judged as moving faster than less attended stimuli. However, our results suggest that this change in visual performance was not accompanied by a corresponding change in the phenomenological appearance of the speed of the moving stimulus.
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Keywords: Attention; Motion perception; Phenomenology

1. Introduction

What we are aware of seeing is what we attend to, since attention profoundly restricts the contents of our limited conscious perception (e.g., Mack & Rock, 1998). Besides determining what we see, does visual attention also affect the way that objects are perceived? Although this has recently become a timely and important question in visual neuroscience (e.g., Carrasco, Ling, & Read, 2004), the question of whether the appearance of objects is modulated by attention was a major issue that characterized the first steps of modern experimental psychology almost a century ago. Indeed, on the basis of independent informal observations, some prominent figures in the this field like William James, Wilhelm Wundt and Hermann Ebbinghaus firmly believed that attention intensifies the sensation of a stimulus (e.g., Ebbinghaus, 1908; James, 1980).

Since then, a few studies have been conducted in the last 30 years that have thoroughly addressed this issue, some of which agreed with the abovementioned view that attention can boost sensation (e.g., Festinger, Coren, & Rivers, 1970); other studies, quite surprisingly, provided evidence to the contrary by showing that, for example, attention reduces the perceived brightness contrast (Tsal, Shalev, Zakay, & Lubow, 1994) and perceived length (Tsal & Shalev, 1996). More recently, the relation between objects' appearance and attention has been reconsidered and investigated by Prinzmetal, Nwachuku, Bodanski, Blumenfeld, and Shimizu (1997). In a series of experiments the authors addressed the effects of attention on perceived contrast and brightness. To overcome possible methodological flaws in previous studies and to obtain a more controlled manipulation of attention allocation, Prinzmetal and colleagues devised a novel experimental procedure based on a dual-task paradigm. On each trial, participants were briefly presented with an array of letters at the centre of the screen, plus a small achromatic disk either to the left or right of the letters. In the (crucial) simultaneous onset condition

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0042-6989/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.visres.2006.10.002

the letters and the disk appeared concurrently, and participants first had to report which of two possible target letters was present, and then they had to indicate the brightness (or contrast) of the disk by adjusting a cursor using one of two vertical brightness response palettes. The main result of Prinzmetal et al. (1997) can be summarized as follows: attending to the stimuli did not make them appear brighter or at higher contrast – namely attention did not alter stimulus' appearance.

In the last 2 years, however, the view that attention does not change the phenomenological appearance of stimuli has been challenged by two studies which reported evidence to the contrary (Carrasco et al., 2004; Gobell & Carrasco, 2005). To study the effect of attention on objects' appearance, Carrasco and her collaborators devised a novel paradigm, which basically stems from that used in other studies in which the effects of covert attention on contrast sensitivity were evaluated (e.g., Cameron, Tai, & Carrasco, 2002; Pestilli & Carrasco, 2005). Shortly, the modified paradigm, which will be used in the present study as well, consists in the brief (about 60 ms) presentation of a peripheral visual onset (the cue) to transiently capture attention to a given location (Nakayama & Mackeben, 1989). About 50 ms later, two stimuli consisting of Gabor patches (sinusoidal achromatic gratings enveloped by a Gaussian filter) of different contrasts and/or spatial frequencies are briefly presented, one on each side of fixation. The task of the observer is to report, for example, the orientation (left vs. right) of the Gabors that appears higher in contrast (Carrasco et al., 2004). If contrast is the feature under investigation, one of the Gabor (referred to as the "standard") has a fixed contrast value, while the other (referred to as the "test") is presented at the same, lower or higher contrast values. To manipulate the spatial allocation of attention in a controlled manner, the cue is randomly delivered either to the standard, the test or at fixation (control condition). By means of this paradigm, which has also been adopted to address the phenomenological effect of attention on the appearance of spatial frequency and gap size (Gobell & Carrasco, 2005), Carrasco et al. (2004) documented that attention can alter the phenomenology of our visual perception. In their study human observers perceived the attended stationary Gabor of a pair as higher in contrast than the less attended one. This is quite a remarkable result, as it shows that visual attention not only plays a crucial role in determining what we are aware of Mack and Rock (1998), but that, to some extent and at least for static stimulus features, attention also affects the way that we see.

One of the most pervasive characteristics common to many stimuli in our visual field is motion. Indeed, in everyday life moving objects are continuously part of our visual experience, such as people moving around us or cars in the street. Moreover, in many circumstances, and for different reasons, we are often required to pay attention to these moving objects, as when we look at the train approaching on the track or a player running in a football game. Hence, the important question we addressed in the present study is whether attention, besides altering the perceived contrast, can also alter the perception of a more complex stimulus property such as motion speed.

Interactions between attention and motion perception have already been documented by using brain imaging and behavioral techniques. Single-cell recording (Martinez-Trujillo & Treue, 2002; Treue & Maunsell, 1996) as well as fMRI studies (Rees, Frith, & Lavie, 1997) have shown that attention modulates neural responses in the motion-related brain area V5/MT. In addition, psychophysical studies have documented that the illusory *motion after-effect* (MAE) is affected by visual attention (e.g., Chaudhuri, 1990). Specifically, in a MAE task participants are first exposed to an adapting moving stimulus, and then to a physically stationary one. Because of the prolonged exposure to visual motion in one direction, the subsequent stationary stimulus is perceived as moving in the opposite direction, an illusion that fades over time. Interestingly, the time course of the MAE has been shown to be sensitive to attention, as less attended adapting stimuli reduce the duration of the corresponding after-effect (Shulman, 1991, 1993). In addition, evidence exists showing that attention not only modulates the duration of the MAE but also its direction. In an elegant experiment Lankheet and Verstraten (1995) presented their participants with two superimposed random dot patterns moving in opposite directions. In the control condition, when attention was not biased to one of the two patterns, no MAE was observed, as the two vectors of movement cancelled each other out in the MAE. However, when attention was deployed to the rightward pattern, for example, the MAE shifted towards the left, thus showing a selective adaptation of the visual system to the attended motion signal. For the attended and non-attended motion signals shared the same location (also see, Alais & Blake, 1999), these results extended those of Chaudhuri (1990), who reported a decrement of the MAE for stimuli at non-attended locations, by showing that the effect of attention on the motion system can take place at feature analysis level rather than being spatially specific.

Although these previous studies nicely documented that attention affects motion perception, so far what has been shown is that attention modulates the adaptability of the visual motion system (e.g., Rezec, Krekelberg, & Dobkins, 2004). Yet, none of them provide evidence for a direct and *phenomenological online* modulation of an attended moving object. Hence, whether or not attention (besides modulating the strength of the MAE) could effectively change the actual appearance of motion perception, and specifically the perceived motion speed, still remains an open issue. In the present study we present five experiments aimed at addressing this issue directly.

2. Experiment 1

As previously anticipated, to address whether attention modulates perceived speed of moving stimuli we adapted the Carrasco et al. (2004) paradigm to the presentation of moving objects. Recently, this paradigm has successfully been used to demonstrate that attention can alter not only the perceived contrast, but also spatial frequency and gap size (Gobell & Carrasco, 2005). In principle, the fact that attention alters the perception of static stimulus properties such as contrast, spatial frequency and gap size, does not logically imply that attention can also change the phenomenology of motion perception. Indeed motion perception is ultimately processed in different neurological brain areas (V5/MT, MST) as compared to those involved in the analysis of the static stimulus properties mentioned above (V1, V2).

In the present study, spatial attention was exogenously attracted to the left or right of fixation via a task-irrelevant cue consisting of a peripheral onset (Jonides, 1981; Nakayama & Mackeben, 1989). After the cue onset, two vertical achromatic sinusoidal gratings briefly appeared, one on each side of the fixation point. The gratings moved either leftward or rightward, and observers were asked to report the direction of movement of the one that appeared to move faster.

2.1. Method

2.1.1. Participants

Eighteen undergraduate students from the University of Trento served as participants. They were compensated either with course credits or 8€ for their participation. All were naïve as to the purpose of the experiment, reported normal or corrected-to normal vision, and gave informed written consent to participate in the study.

2.1.2. Apparatus

Participants sat approximately 60 cm in front of an iiyama CRT 19″ (1024 × 768, 150 Hz) monitor. Generation and presentation of the stimuli was controlled by a custom-made program written using Matlab and the Psychophysics Toolbox (Pelli, 1997), and running under Windows 2000 on a Pentium IV Dell PC. In addition, to ensure that fixation was maintained throughout the trial, eye movements were monitored and recorded by an Eyelink II system (SR Research, Ont., Canada). Head movements were restrained by using a cheekbone and chin rest device.

2.1.3. Stimuli and procedure

The stimuli were presented over a grey background (27.7 cd/m^2). As shown in Fig. 1, each trial started with the presentation of a black fixation point (a disk subtending 0.2° of visual angle) in the centre of the screen, and participants had to maintain their gaze at fixation throughout the trial. 1000 ms later a visual onset (the cue) consisting of a black disk (0.6°) was transiently presented for 59 ms. The cue could appear either at fixation (control condition), or just above (2° vertically) one of the two peripheral positions (4° left or right of fixation) where the target stimuli appeared 53 ms later (see Fig. 1). The target stimuli

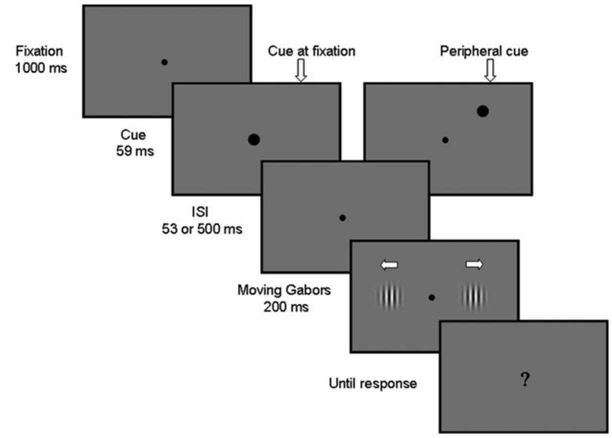

Fig. 1. Example of the events occurring on each trial in the attentional (peripheral cue) and control (cue at fixation) conditions, respectively. The two horizontal white arrows (which were not present in the display) indicate the direction of motion of the two Gabors. In this example both Gabors moved outward but in opposite directions. The stimuli are not drawn to scale.

consisted of two Gabor patches (vertical sinusoidal achromatic gratings enveloped by a Gaussian filter; 3° × 3°) presented for 200 ms 4° to the left and right of fixation. The Gabors' motion was achieved by independently shifting the two gratings leftward or rightward. One of the two Gabors (the standard) moved at a fixed speed (4.29°/s), whilst the other (the test) moved at seven different possible speeds (1.88, 3.13, 3.75, 4.29, 5.02, 6.82, or 15°/s). The speeds were preliminarily determined in a pilot study, and were chosen as to create a sigmoid-like function in the control condition.

The contrast of the Gabors was 60%. Once the Gabors disappeared a question mark replaced the fixation point, signalling participants to report (see below) the direction of movement of the Gabor that they judged to have moved faster. The next trial began 1000 ms after the participants' response.

Participants performed a 2 × 2 alternative forced choice task: if the left Gabor was perceived as being faster, they responded with their left hand by pressing the "Q" key (middle finger) or the "W" key (index finger) depending on whether motion was leftward or rightward, respectively. By contrast, if the right Gabor was perceived as being faster, they responded with their right hand by pressing the "O" key (index finger) or the "P" key (middle finger) depending on whether motion was leftward or rightward, respectively. Hence, though we asked participants to report the direction of motion, we were actually interested in their perception of motion speed. As pointed out by Carrasco et al. (2004), this method has the advantage of reducing any possible response bias in the dimension of interest (here speed of motion).

2.1.4. Design

A 3 × 7 factorial design was used, with cue condition and test speed as factors. The cue condition had three levels (test, control, standard), whilst the test speed condition had seven levels (see above). In total each participant performed 672 experimental trials (32 trials per condition) divided in four blocks of 182 trials each. In addition, before the first block began observers performed 40 practice trials; 10 warm-up trials were completed before each new block. Practice and warm-up trials were not included in the data analysis. The experiment took about 75 min to be completed.

2.2. Results

We calculated the proportion of trials in which the test Gabor appeared to move faster than the standard Gabor as a function of whether attention was cued to the test, the standard, or remained at fixation (control condition). Results depicted in Fig. 2a (where each curve was generated by a Gaussian fit of the corresponding data. The horizontal line intersecting the curves indicates the Point of Subjective Equivalence, *PSE*) show that visual attention increased the perceived speed of motion over a wide range of speeds. This effect was confirmed by a statistical analysis of variance (ANOVA) with cue and test speed as factors. The factor test speed was significant $F(6,102) = 256.693$, $p < .0001$, indicating that the participants' ability to appreciate a difference in speed between the test and the standard was maximal when the test was clearly slower or faster as compared to the standard, while it was minimal when the two Gabors had approximately the same velocity. Crucially, we also observed a significant main effect of cue condition $F(2,34) = 15.233$, $p < .0001$, indicating a change in participants' performance as a function of attention. Accordingly, as compared to the control condition ($PSE = 4.35°/s$, $SD = 1.65$), the test-cued curve shifted to the left ($PSE = 3.85°/s$, $SD = 1.81$), whilst the standard-cued curve shifted to the right ($PSE = 4.84°/s$, $SD = 1.67$). In other words, on the one hand when attention was allocated to the test, it was judged to have the same speed as the standard even though it actually moved at a slower speed. On the other hand, when attention was directed to the standard, the test needed to move at a higher speed to be seen as moving at the same speed as the standard. In both cases the attended Gabor was perceived as moving faster than the less attended one. However, as one may note the difference in speed produced by attention was, on average, 0.50°/s, a value that was smaller than the average just noticeable difference (*JND*) in the control condition ($JND = 1.1°/s$, calculated as half the difference between the speeds at the 25% and 75% cutoffs). These results may suggest that although participants consistently and reliably reported the attended Gabor as moving faster, it is likely that they were not able to consciously appreciate the difference in speed produced by attention. In Experiments 5a and 5b we will address this issue directly.

The interaction between the two factors was also significant $F(12,204) = 5.703$, $p < .0001$, which indicates that the effect of attention on the perceived speed of motion tended to be reduced for the extreme values of motion speeds. This suggests that under the present experimental conditions (i.e., levels of speed) the increment in the perceived speed of the attended Gabor was not large enough for observers to perceive the test Gabor as moving faster than the standard Gabor when the difference in the actual speed between the two stimuli was very large (e.g., standard = 4.29°/s vs. test = 15°/s). Finally, the same main effects and the interaction were significant even when test vs. control and standard vs. control conditions were considered separately (all $ps < .005$).

To sum up, since participants judged the attended moving stimulus to move faster than the unattended moving stimulus, the results of Experiment 1 indicate that attention can alter the perception of visual stimuli, not only by

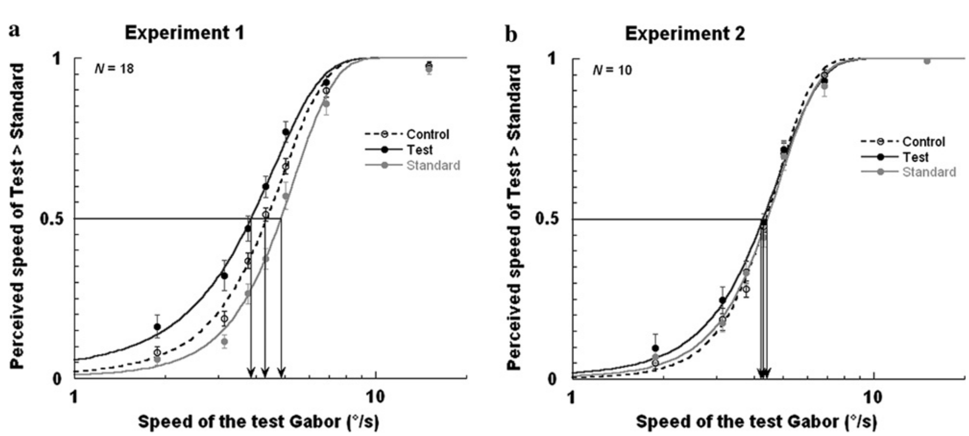

Fig. 2. (a) Results of Experiment 1 (53-ms ISI). Proportion of responses in which observers reported the speed of the test Gabor as faster than the standard Gabor, plotted as a function of the test Gabor's physical speed for the three cueing conditions. The standard Gabor moved at a fixed speed: 4.29°/s. The three downward-pointing arrows indicate the test speed necessary for both stimuli to be perceived as moving at the same speed (*PSE*). When either the test or the standard were cued, the *PSE* shifted to the left or right, respectively, indicating that the attended stimulus was judged as moving faster. (b) Results of Experiment 2 (500-ms ISI). When attention was no longer at the cued location because of the long cue-Gabor interval, the three plots and the corresponding *PSE*s coincided. The curves in (a) and (b) are Gaussian fits of the data.

increasing their perceived contrast (Carrasco et al., 2004), spatial frequency or gap size (Gobell & Carrasco, 2005), but also by altering the perceived speed of motion.

3. Experiment 2

The pattern of results from Experiment 1 points to a modulation of the perceived speed of motion by attention. In order to confirm that this result was a genuine attentional modulation of perceived motion speed we needed to rule out an alternative explanation in terms of a decision bias toward the stimulus sharing the same position as the cue. In other words, it may be that when observers were uncertain as to which was the faster Gabor, they could have adopted a decision bias that tended to favor the selection of the Gabor sharing the same spatial location as the cue. To exclude this possibility, in the present experiment we extended the inter stimulus interval (ISI) between the cue and the Gabors to 500 ms. This manipulation was motivated by the fact that it is well established that the exogenous orienting of attention is a very short-lived phenomenon vanishing within 250 ms from cue onset (Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). So, if the results observed in Experiment 1 were due to attention and not to a decisional bias, by extending the ISI up to 500 ms the prediction is that the effect of the cue on motion perception should vanish. On the contrary, if the results of Experiment 1 were generated by a decision bias, the same pattern of results are expected also with an ISI of 500 ms (also see, Carrasco et al., 2004).

3.1. Method

3.1.1. Participants

Ten undergraduate students from the University of Trento served as participants. They were compensated either with course credits or 8€ for their participation. All were naïve as to the purpose of the experiment, reported normal or corrected-to normal vision, and gave informed written consent to participate in the study. None had taken part in Experiment 1.

3.1.2. Apparatus, stimuli, design, and procedure

Everything was the same as in Experiment 1, with the exception that the ISI was increased up to 500 ms.

3.2. Results

Fig. 2b depicts the participants' performance in the test-cued, standard-cued and control conditions (each curve was generated by a Gaussian fit of the corresponding data) Results differed substantially from those in Fig. 2a (53-ms ISI), and showed that with a 500-ms ISI, participants' responses no longer varied as a function of the cue condition, and that any effect of the cue disappeared. This was confirmed by a further ANOVA which revealed only a significant main effect of test speed $F(6,54) = 236.418$, $p < .0001$. However, the crucial main effect of cue, as well as the interaction with test speed were not significant (with the lowest $p = .371$). The lack of any cue effect on visual (motion) perception with an ISI of 500 ms is what one would have expected if attention, and not a decision bias, accounted for the results of Experiment 1. Indeed, previous studies on the temporal dynamics of attentional capture have clearly documented that sudden visual onsets, such as that used here, summon attention to the corresponding location for no longer than 200 ms. After such an interval the facilitatory effects of attentional capture decay very rapidly (Jonides, 1981; Nakayama & Mackeben, 1989). In addition, the present findings are in agreement with what was reported by Carrasco et al. (2004) for the perception of contrast when an ISI of 500 ms was used.

4. Experiment 3

The results of Experiment 2 suggested that the decision-bias account can probably be dismissed. However, one may note that in Experiment 2 we changed the ISI between the cue and the Gabors, and that this could have affected, beside attentional allocation, other low-level visual interactions between the cue and the Gabor sharing the same spatial location. As already proposed by Carrasco et al. (2004), to circumvent this problem in the present experiment we kept the same 53-ms ISI used in Experiment 1, but instead of asking participants to report the direction of motion of the faster Gabor, we required them to report the direction of motion of the *slower* Gabor. In these conditions, any low-level visual interactions between the stimuli in the display are preserved as in Experiment 1, and crucially, the attentional- and decision-bias accounts make opposite predictions. If the results of Experiment 1 were merely due to a bias in selecting the cued Gabor, then we should expect participants to select the cued Gabor also when the task requires them to indicate the slower instead of the faster one. By contrast, if attention is responsible for the effect reported in Experiment 1, then one should expect participants to perceive the uncued Gabor as the slower stimulus.

4.1. Method

4.1.1. Participants

Twelve undergraduate students from the University of Trento served as participants. They were compensated either with course credits or 8€ for their participation. All were naïve as to the purpose of the experiment, reported normal or corrected-to normal vision, and gave informed written consent to participate in the study. None had taken part in Experiments 1 or 2.

4.1.2. Apparatus, stimuli, design, and procedure

Everything was the same as Experiment 1, with the following exceptions: First, participants had to report the direction of motion of the slower Gabor; second, in order to reduce the overall duration of the experiment we used only the control and standard-cued condition.

4.2. Results

We calculated the proportion of trials in which the test Gabor appeared to move slower than the standard Gabor, as a function of whether attention was cued to either the standard or remained at fixation (control condition). Results depicted in Fig. 3a (where each curve was generated by a Gaussian fit of the corresponding data) confirmed that visual attention increased the perceived speed of motion when participants had to report the direction of motion of the slower Gabor. An ANOVA with cue and test speed as factors revealed that the factor test speed $F(6,66) = 66.137$, $p < .0001$, and crucially the factor cue $F(1,11) = 10.868$, $p < .007$, were significant. This latter result documented a change in participants' performance as a function of attention that was consistent with the result of Experiment 1, in which the task required to judge the direction of motion of the faster Gabor. Accordingly, as compared to the control condition ($PSE = 4.25°/s$; $SD = 2.91$), the curve in the standard-cued condition shifted to the right ($PSE = 4.72°/s$; $SD = 2.77$), indicating that when the standard was cued, the test was more often selected as the slower stimulus. The interaction between the two factors only approached significance $F(6,66) = 2.105$, $p = .064$.

On the basis of the results of the present experiment we can safely dismiss the decision-bias account. Indeed, if a decision bias, namely a tendency to select the cued Gabor, was responsible for the findings of Experiment 1, then the same bias in favor of the cued Gabor should have emerged in the present experiment as well; this was clearly not the case.

5. Experiment 4

Although the findings from Experiments 2 and 3 allowed us to rule out a decision bias as an explanation of the results of Experiment 1, one additional alternative interpretation must be dismissed before we can conclude that visual attention modifies the perceived speed of moving objects.

Recently it has been shown that visual attention alters the perceived contrast of the stimulus, so that the attended stimulus of a pair is judged as being higher in contrast than the less attended one (Carrasco et al., 2004). Furthermore, previous psychophysical studies have established that the perceived speed of moving gratings is affected by contrast, so that gratings at higher contrast are perceived as moving faster than gratings at lower contrast (e.g., Thompson, 1982; Stone & Thompson, 1992; but see McKee, Silverman, & Nakayama, 1986). Hence, one might reasonably argue that what we documented in Experiment 1 was not a direct modulation of perceived motion speed by visual attention, but rather the consequence of increasing the perceived contrast of the attended Gabor, which, in turn, caused the perceived increment in motion speed. Therefore, at this point we are left with the following two possibilities: either attention directly alters the perceived speed of moving gratings, or alternatively, such an effect is due to a change in the perceived contrast of the attended moving Gabor. Distinguishing between these two accounts may be relevant to understanding at what stage of information processing, and possibly in which neural site(s) in the visual system

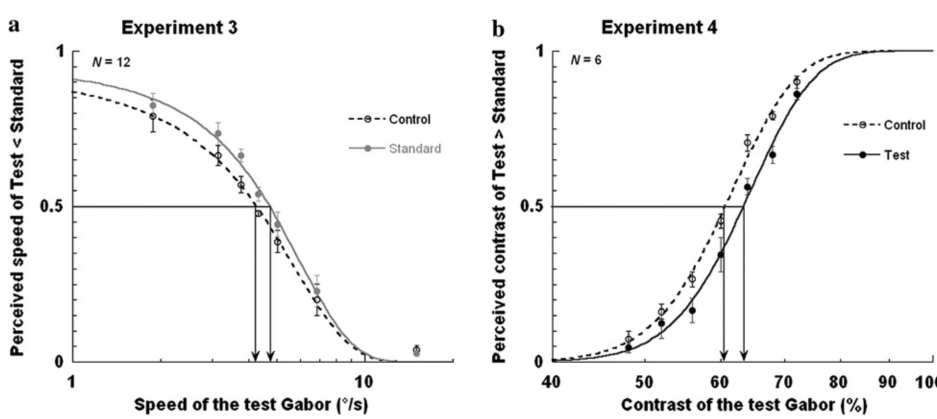

Fig. 3. (a) Results of Experiment 3. Proportion of responses in which observers reported the speed of the test Gabor as slower than the standard Gabor, plotted as a function of the test Gabor's physical speed for the two cueing conditions. The standard Gabor moved at a fixed speed: 4.29°/s. The two downward-pointing arrows indicate the *PSE* in the control and standard conditions. As compared to the *PSE* in the control condition, when the standard was cued, the *PSE* shifted to the right, indicating that the attended stimulus was less likely to be judged as moving slower, or put differently that the unattended stimulus (the test in the present experiment) was more likely to be perceived as moving slower. (b) Results of Experiment 4. Proportion of responses in which observers reported the contrast of the test moving Gabor as higher than the standard moving Gabor, plotted as a function of the test Gabor's physical contrast for the two cueing conditions. The two Gabors moved at a fixed speed (4.29°/s), while the standard Gabor had a fixed contrast (60%). The two downward-pointing arrows indicate the test contrast necessary for both stimuli to be perceived as having the same contrast (*PSE*). As compared to the *PSE* in the control condition, when the test was cued, the *PSE* shifted to the right, indicating that the attended stimulus was less likely to be judged as higher in contrast. The curves in (a) and (b) are Gaussian fits of the data.

attention can affect the perception of motion speed. One should note, however, that the view according to which the boost up in perceived motion speed is the consequence of a change in the perceived contrast of the attended Gabor rests on the assumption that the contrast of moving gratings, as that of static ones (Carrasco et al., 2004), is increased by visual attention. Since, to the best of our knowledge, there is no empirical evidence supporting this (plausible) assumption, we devised an experimental procedure aimed at directly addressing whether the contrast of moving sinusoidal gratings is altered by visual attention. If this were the case, our next step would be to distinguish whether the increment in perceived motion speed was totally attributable to a change in contrast, or whether attention can, at least partially, alter the perception of motion speed directly. On the other hand, however, if the contrast of a moving Gabor is not increased by visual attention, then there is no point in assuming that the boost in the perception of motion speed we reported was caused by a change in the perceived contrast of the attended moving Gabor.

5.1. Method

5.1.1. Participants

Six undergraduate students from the University of Trento served as participants. They were compensated either with course credits or 8€ for their participation. All were naïve as to the purpose of the experiment, reported normal or corrected-to normal vision, and gave informed written consent to participate in the study. None had taken part in previous experiments.

5.1.2. Apparatus, stimuli, and procedure

The same paradigm used in Experiment 1 was adapted to study whether attention alters the apparent contrast of moving Gabors. In other words, we used the basic paradigm proposed by Carrasco et al. (2004), except that our stimuli were moving Gabors (4.29°/s) instead of stationary. We used only the control and test-cued condition, so as to maximize the number of data points per cell in the design, while keeping the overall duration of the experiment below 1 h. We kept the contrast of the standard Gabor fixed (60%), and varied that of the test Gabor from trial to trial using seven levels of contrast (48%, 52%, 56%, 60%, 62%, 68%, and 72%). The contrast levels were preliminarily determined in a pilot study as to create a sigmoid-like function in the control condition. Participants were instructed to report the direction of movement (left vs. right) of the Gabor that looked higher in contrast.

5.1.3. Design

A 2×7 factorial design with cue and test contrast as factors. The factor cue had two levels (test and control), whilst the factor test contrast had seven levels (see above). In total each participant performed 560 experimental trials (40 trials per condition) divided into five blocks of 112 trials each. In addition, before the first block began observers performed 20 practice trials, and five warm-up trials were completed before each new block. Practice and warm-up trials were not included in data analysis.

5.2. Results

We calculated the proportion of trials in which the test Gabor appeared to be higher in contrast than the standard Gabor, as a function of whether attention was cued to the test or remained at fixation (control condition). Results, depicted in Fig. 3b (where each curve was generated by a Gaussian fit of the corresponding data), showed that the cued Gabor was not seen as being higher in contrast as compared to the uncued one. Instead, since the curve in the test cued condition shifted to the right of the curve in the control condition, Fig. 3b suggests that, quite surprisingly, the attended Gabor was perceived as lower in contrast. This impression was confirmed by an ANOVA in which both the main effect of test contrast $F(6,30) = 290.000$, $p < .0001$, and cue $F(1,5) = 10.224$, $p < .024$ were significant. In other words, participants judged the attended moving Gabor as being lower in contrast (control condition, $PSE = 60.63$, $SD = 8.3$; test cued condition, $PSE = 63.33$, $SD = 8.6$), a result that, as discussed in detail later, is the opposite of what Carrasco et al. (2004) found when the Gabors were stationary. The interaction between the two factors only approached significance $F(6,30) = 2.279$, $p = .062$, suggesting that the effect of attention in biasing the participants' response was limited or absent when the physical contrast difference between the cued and uncued Gabor was very large.

The present results definitely undermine the possibility that the boost in perceive speed observed in Experiment 1 can be attributed to an increment in the perceived contrast of the attended moving Gabor. Indeed, this view would have predicted a pattern of results opposite to that which emerged in the present experiment; namely observers should have reported the attended Gabor as being higher in contrast. Therefore, we can safely conclude that attention can directly alter the perceived speed of the selected stimulus. The fact that participants reliably selected the unattended Gabor as the highest in contrast could be due to the fact that attention, by increasing the perceived speed of the cued Gabor, increased also the blurring of the corresponding image, which in turns might have reduced its contrast.

6. Experiment 5a

The experiments presented so far provide converging evidence that attention increases perceived motion speed. This finding is in agreement with those of recent studies showing that, when participants are asked to report which stimulus of a pair is higher in contrast, or spatial frequency, observers exhibited a significant bias in favor of the cued stimulus as compared to the uncued one (Carrasco et al., 2004; Gobell & Carrasco, 2005). Crucially, in these studies, and particularly in the study by Carrasco et al. (2004), it has been claimed that this result can be accounted for by a change in the phenomenological appearance of the attended stimulus, so that participants actually saw the attended Gabor as being, for example, higher in contrast. Therefore, one may wonder whether the effect of attention on motion speed perception was also due to a change in the phenomenological appearance of the stimuli. Alternatively, the difference may be due *only* to a change in visual performance. Put differently, did participants consciously and genuinely see the attended Gabor as moving faster than the less attended one, or was their performance based on *implicit* speed perception? The fact that in Experiment 1 the estimated effect of attention was smaller than the *JND* is consistent with the latter possibility. However, to directly address this issue participants were presented with two Gabors moving either at the same or different speeds, and were asked to report whether they noted a speed difference between the two Gabors. So, instead of forcing participants to report which was the faster Gabor of a pair, as we did in previous experiments, here we asked participants to respond on the basis of their phenomenological awareness, if any, of a difference in speed between the two stimuli.

6.1. Method

6.1.1. Participants

Four undergraduate students from the University of Trento, plus two of the authors (M. T. and M. Ve.) served as participants. The four students were compensated either with course credits or 8€ for their participation, and were naïve as to the purpose of the experiment. All participants reported normal or corrected-to normal vision, and gave informed written consent to participate in the study. None had taken part in previous experiments.

6.1.2. Apparatus, stimuli, and procedure

The paradigm used in Experiment 1 was modified as follows. First, no cue was presented; second, in the same-speed condition both Gabors moved at 4.29°/s (the standard speed used in previous experiments), whereas in the different-speed condition one Gabor moved at 4.29°/s, whilst the other moved at one of four different speeds (two slower and two faster than the standard speed): 3.75, 3.96, 4.70, or 5.02°/s. The slowest (3.75°/s) and the fastest (5.02°/s) speeds were already used in Experiment 1 as those closest to the standard speed. The remaining two intermediate speeds (3.96 and 4.70°/s) were chosen as the best matching *PSE-speed* in the test-cued (3.85°/s) and standard-cued (4.85°/s) condition, as observed in Experiment 1. In other words, as compared to the control condition, they approximately corresponded to the increment and decrement of the standard speed caused by visual attention.

Participants were instructed to press the "B" key on the computer keyboard if they saw a difference in speed between the two Gabors, and the "N" key if they saw the two Gabors moving at the same speed.

6.1.3. Design

Participants were submitted to 128 trials in the different-speed condition (32 trials for each speed) and to 128 trial in the same-speed condition, divided into two blocks. In addition, before the first block of trials observers performed 20 practice trials, which were not included in the data analysis.

6.2. Results

Overall participants reported that it was very difficult, if not impossible, to consciously appreciate any speed difference between the two Gabors. However, to obtain an objective measure of the participants' capacity to detect speed differences, data were analyzed using a measure of signal sensitivity (d'; Green & Swets, 1974). The proportion of trials in which participants correctly detected a speed difference between the Gabors (*Hits*), and the proportion of trials in which they reported a difference while the two Gabors had the same speed (*False alarms*) were used to calculate d' and β for each of the four speed levels. In order to gain statistical power, before comparing d' mean scores with 0 (lack of sensitivity) and β mean scores with 1 (no bias in the response criterion), we averaged together data from the two speeds (3.96 and 4.70°/s) corresponding to the *PSE* values into "speed-difference 1" condition, and data from the slowest and fastest speeds (3.75 and 5.02°/s) into "speed-difference 2" condition. Results showed that in both conditions d' was not significantly different from 0 (speed-difference 1, $d' = 0.07$, $p = .184$; speed-difference 2, $d' = 0.13$, $p = .128$); β was not significantly different from 1 in both conditions.

Although the results of Experiment 1 documented a reliable boost up of the speed of motion of the attended Gabor, on the basis of the findings of the present experiment it seems hard to conclude that attention altered the phenomenological appearance of the speed of the cued Gabor. However, the participants' inability to consciously perceive a speed difference in the present experiment is not inconsistent with the fact that, for the same speed difference, they correctly selected the faster Gabor when forced to do so in Experiment 1. These apparent discrepant outcomes can probably be reconciled by noticing that the procedure adopted in Experiment 1 always forced participants to guess which was the faster Gabor, and this even when in the control condition the difference in speed between the standard and the test was minimal (as in speed-difference 2 condition of the present experiment), or when one of the two Gabors having similar speeds was cued. In these conditions it is likely that participants were not aware of having seen a difference in speed between the two Gabors. Therefore, what we likely measured when we cued a Gabor was the effect of attention on visual performance regardless of any visual awareness. By contrast, in the present experiment by asking participants to report whether they noted any difference in speed between the two Gabors, we directly addressed their phenomenological awareness of a difference in speed. Put differently, it is likely that while Experiment 1 relied more on *perception without awareness*, Experiment 5a was more concerned with *conscious perception*. The dissociation between perception with and without awareness is well documented in cognitive psychology, and as discussed later there are several cases in which human beings exhibit visual performance above chance in the absence of awareness (Merikle, Smilek, & Eastwood, 2001).

In the next experiment (5b) we tried to provide further support for this hypothesis. To this aim we presented participants with the same speed values used in Experiment 5a, but instead of asking participants to report any difference in speed between the two Gabors, we asked them to decide which one was faster. Our prediction was that, regardless of any awareness of speed difference, under this condition participants' performance should vary from chance, or, in other words, their sensitivity (d') to difference in speed should be significantly higher than zero.

7. Experiment 5b

7.1. Method

7.1.1. Participants

Five undergraduate students from the University of Trento, plus two of the authors (M. T. and M. Ve.) served as participants. The five students were compensated either with course credits or 8€ for their participation, and were naïve as to the purpose of the experiment. All participants reported normal or corrected-to normal vision, and gave informed written consent to participate in the study. With the exception of the two authors none of the participants had taken part in previous experiments.

7.1.2. Apparatus, stimuli, and procedure

As in Experiment 5a, except that participants were instructed to report the direction of movement (left vs. right) of the fastest Gabor (see Experiment 1 for details).

7.1.3. Design

Participants were submitted to 48 trials in each of the five speed levels (3.75, 3.96, 4.29, 4.70, and 5.02°/s), for a total of 240 trials divided into 3 blocks of 80 trials each. In addition, before the first block of trials participants performed 20 practice trials, which were not included in the data analysis.

7.2. Results

When informally probed at the end of the experiment, participants reported that they had guessed which Gabor moved faster, as it was very hard if not impossible to consciously perceive a speed difference between the two Gabors. We calculated d' (using the formula for the 2AFC discrimination tasks, $d' = [z(\text{Hit}) - z(\text{FA})]/\sqrt{2}$) for each of the four speed levels in which the two Gabors had different speeds (3.75, 3.96, 4.70, and 5.02°/s). To this aim we treated the condition in which the faster Gabor was on the left as "signal", and that in which the faster Gabor was on the right as "noise": *Hits* were considered those trials in which participants correctly reported the left Gabor as being faster; *False alarms* were those trials in which participants selected the left Gabor when in fact the faster was on the right. As in the previous experiment, to gain statistical power we averaged together data from the two speeds (3.96 and 4.70°/s) corresponding to the *PSE* values into the "speed-difference 1" condition, and data from the slowest and fastest speeds (3.75 and 5.02°/s) into the "speed-difference 2" condition. d' values were 0.45 and 0.50 in the speed-difference 1 and 2 conditions respectively, and in both cases d' was significantly different from 0 (all $ps < .011$).

Hence, despite participants claiming that they were not aware of having seen any speed difference, as expected, when they were forced to decide which Gabor moved faster their performance was not at chance, as d' results showed that the visual system *implicitly* recognized the faster Gabor. Note that this finding was obtained for the same speed values for which, when required to report whether or not a difference in speed was present (Experiment 5a), participants' sensitivity was not different from zero.

8. General discussion

After more than a century of research on visual attention it is well established that attention affects different aspects of visual analysis. However, to date the scientific enterprise committed to the understanding of attentional phenomenon has mainly focused on how attention affects visual performance (e.g., in terms of speed or accuracy) rather than addressing whether the phenomenological appearance of visual objects can be shaped by attention. Indeed, the effects of attention on visual performance have been documented on response times (e.g., Posner, 1980), accuracy (e.g., Bashinski & Bacharach, 1980; Lyon, 1990), spatial resolution (e.g., Yeshurun & Carrasco, 1999), rate of information accrual (Carrasco & McElree, 2001), and contrast sensitivity (e.g., Cameron et al., 2002; Lu & Dosher, 1998; Treue, 2004). Although there is no doubt that attention improves the efficiency of visual analysis (but see Yeshurun & Carrasco, 1998), it remains an open issue as to whether attention also alters the phenomenological appearance of visual stimuli. In other words, does an attended stimulus look different compared to a less attended one?

This intriguing question was considered, more than a century ago, by famous pioneers of modern experimental psychology like Wundt, James and Ebbingaus, who believed and suggested that attended stimuli should be perceived more vividly compared to less attended stimuli (e.g., Ebbinghaus, 1908; James, 1980). In the last decade, this important issue has been tackled by Prinzmetal and colleagues (Prinzmetal et al., 1997), whose work, however, seemed to provide evidence that attention does not alter the phenomenological appearance of stimuli. Yet, as noted by

Carrasco et al. (2004) some methodological aspects of the experimental procedure used in the Prinzmetal et al. (1997) study may have precluded the possibility of demonstrating the effect of attention on stimuli's appearance. Perhaps the most important concerns associated with Prinzmetal et al.'s study regard the lack of a precise control of the allocation of attention in space, the unclear contribution of eye movements, and an unlimited response time. To assess the role of attention on the appearance of the stimuli by overcoming these potential methodological flaws, Carrasco et al. (2004) devised a different procedure, in which spatial attention was cued to a given location via a peripheral visual onset prior to the targets' occurrence. The interval of time between the cue and the targets (~70 ms) was chosen so as to magnify the effect of transient-automatic attention (Jonides, 1981; Nakayama & Mackeben, 1989), and to preclude, given the brief ISI (~50 ms) and target presentation time (40 ms), any effect of eye movements. In addition, the procedure proposed by Carrasco and colleagues required a direct online comparison between the perceived contrast of two concurrently presented targets, thus directly evaluating a possible phenomenological difference in appearance between the attended and less-attended target stimuli. In these experimental conditions Carrasco et al. (2004) showed that attention altered the perceived contrast of the cued Gabor, which was judged to be higher in contrast. In a following study (Gobell & Carrasco, 2005) the same procedure that proved to be successful in showing that attention alters the perceived contrast was adapted to demonstrate that other static features, such as spatial frequency and gap size, can also be altered by visual attention. Specifically, the authors provided evidence that transient attention increased the apparent spatial frequency of the selected Gabor stimulus, and increased apparent gap size in a Landolt-square acuity task.

These findings, which testified that attention can change the appearance of static visual stimuli, encouraged us to address whether attention can also modify the perceived speed of moving stimuli. Indeed, besides contrast, spatial frequency and gap size, motion is another important visual property of many objects or events that we usually encounter in our everyday visual experience.

With regard to possible interactions between attention and visual motion perception, neuroimaging studies have already documented a role of attention in shaping the neural responses in motion-sensitive cortical areas (e.g., Martinez-Trujillo & Treue, 2002; Treue & Martinez-Trujillo, 1999; Treue & Maunsell, 1996). For example, it has been shown that the neural activity in V5/MT associated with the MAE produced by exposure to distracting moving dots in the background was strongly attenuated, if not completely abolished, when attention was diverted from motion processing by engaging participants' attention in a highly demanding linguistic task at the center of the screen (Rees et al., 1997). In addition, psychophysical studies have shown that attending to a pattern of moving stimuli increases the duration (Chaudhuri, 1990) and direction (Alais & Blake, 1999; Lankheet & Verstraten, 1995) of the corresponding MAE, and enhances the effect of adaptation to motion processing (Rezec et al., 2004).

However, since no previous study has addressed whether attention can directly alter the perception of motion speed, we decided to investigate this issue directly. To this purpose, we used the basic paradigm proposed by Carrasco et al. (2004), which was adapted to study motion speed perception. Instead of using static Gabors, we presented two moving Gabors, where motion was achieved by independently shifting the two sinusoidal gratings leftward or rightward. The impact of attention on motion speed perception, if any, was assessed by cueing one Gabor and by asking participants the direction of motion (left vs. right) of the faster Gabor. The result of Experiment 1 showed that when the test and the standard Gabors moved at the same physical speed, participants overestimated the motion speed of the attended Gabor by approximately 10%. Indeed, as compared to a *PSE* of 4.35°/s in the control condition, when the test was attended, the corresponding *PSE* decreased to 3.85°/s (see Fig. 2a). By contrast, when the standard was cued the *PSE* of the test increased to 4.84°/s. So, in line with previous findings on perceived contrast, these results support the hypothesis that attention increased the perceived speed of a moving stimulus.

We then devised two control experiments to rule out the possibility that such findings could be accounted for by a decision bias rather than a change in perception (also see Carrasco et al., 2004). Specifically, Experiment 2 showed that the effect disappeared when the ISI between the cue and the Gabors was increased to 500 ms (see Fig. 2b), a result consistent with the temporal dynamic of transient attention (Nakayama & Mackeben, 1989). In addition, and most crucially, when participants were asked to indicate the direction of motion of the slower Gabor (Experiment 3), they showed a significant perceptual bias in favor of the uncued Gabor (see Fig. 3a). This result was the opposite than that predicted by the decision-bias hypothesis, which would have predicted that the cued Gabor always has higher chances of being selected regardless of whether observers were required to report the faster or the slower Gabor. However, this result was not sufficient to completely rule out the decision-bias account. One might argue, for instance, that participants were more prone to select a stimulus as the one that has *more* rather than *less* of a given feature (here speed) when it coincides with attention. By contrast, they might have had the tendency to associate the stimulus that had *less* rather than *more* of a feature with the uncued location. This, in principle, could explain why, in Experiment 3, participants tended to report the Gabor at the uncued location as slower, i.e., the one that was "not faster" or that possessed *less* speed. However, this further alternative decision-bias interpretation was ruled out by the results of Experiment 4.

The main purpose of Experiment 4 was to verify whether the increment in perceived motion speed for the cued Gabor reported in Experiment 1 was a direct and genuine effect of attention on speed perception. Indeed, because stimuli at higher contrast are seen as moving faster (e.g., Stone & Thompson, 1992; Thompson, 1982; Thompson, Stone, & Swash, 1996), and given that attention increases perceived contrast (Carrasco et al., 2004), one could argue that the increment in motion speed we reported might be a secondary effect of attention boosting contrast, and therefore the perceived speed. Even though this argument might be plausible, it rests on the assumption that attention, besides increasing the perceived contrast of a static Gabor, would also increase the perceived contrast of a moving Gabor. Hence, our goal was to directly verify whether this was the case. To this aim, in Experiment 4 we implemented essentially the same procedure used to study perceived contrast with static Gabors, except that our stimuli were two Gabors drifting at the same constant speed. We asked participants to report which Gabor looked higher in contrast, and quite surprisingly we found that the attended Gabor was judged to appear lower in contrast. This result has at least two important implications. First, it excludes a version of the decision-bias account that assumes a tendency to select the Gabor at the uncued location if it can be associated with a negative dimension. Indeed, if on the one hand in Experiment 3 observers judged the uncued Gabor as the one that was slower (i.e., not faster), on the other hand in Experiment 4 they still selected the uncued Gabor when asked to report the one that was higher in contrast. Second, the data from Experiment 4 provide evidence that attention *reduces* the perceived contrast of a moving Gabor, a result that is opposite to what has been reported by Carrasco et al. (2004) with static Gabors. Why would attention decrease the perceived contrast of a moving Gabor? Although we do not have a straightforward explanation, one could speculate that the increased perceived speed of the cued Gabor might have caused a larger degree of blurring in the corresponding image, thus likely reducing its contrast (see however, Burr & Morgan, 1997). However, while further experimental work should be aimed at addressing this issue more directly, this finding rules out the possibility that the increase in speed reported in Experiment 1 was a secondary effect of a change in apparent contrast.

The perceived speed of a moving sinusoidal grating is affected by its contrast and spatial frequency. However, while increasing contrast of a grating increases its perceived speed (Stone & Thompson, 1992), increasing spatial frequency decreases the perceived speed (Smith & Edgar, 1990; also see Priebe & Lisberger, 2004). Interestingly, Gobell and Carrasco (2005) have recently shown that attention increases the perceived spatial frequency of static Gabors. Hence, if in principle attention might increase the contrast of the cued Gabor, which in turn may result moving at higher speed (but see the results of Experiment 4), the results of Gobell and Carrasco (2005) would predict that in Experiment 1 the attended Gabor should have been perceived at higher spatial frequency, which should have caused a reduction of the corresponding perceived speed. The results of Experiment 1 clearly showed that this was not the case; those data suggest that speed perception is not secondary to effect of attention on the spatial frequency of the moving Gabor, probably because it may be difficult to estimate (consciously or unconsciously) small changes in the spatial frequency of a moving grating.

So, the influence of static stimulus properties (contrast and spatial frequency) on motion speed perception, and the interactions between these factors and attention can be summarized as follows: (a) attention increases perceived contrast (Carrasco et al., 2004); (b) increasing contrast increases perceived speed (Stone & Thompson, 1992); (c) attention increases perceived spatial frequency (Gobell & Carrasco, 2005); (d) increasing spatial frequency decreases perceived speed (Smith & Edgar, 1990); but attention increases perceived speed (Experiment 1), and attention decreases perceived contrast of moving stimuli (Experiment 4). Since with moving Gabors the attended one was judged as being lower in contrast, and given that the perceived speed is positively correlated with the degree of contrast (at least with static Gabors), one may hypothesize that participants might have underestimated the perceived speed of the attended Gabor, thus reducing, if any, the observed effect of attention on motion speed perception reported in Experiment 1. In any case, this result suggests that the modulation of speed we documented was a direct effect of attention on speed perception.

A final issue that emerged from the results of the present study regards the change in the phenomenological appearance of the attended stimuli. In the case of the effect of attention on perceived contrast, Carrasco et al. (2004) stressed the fact that their findings demonstrated that attention effectively alters the way participants *consciously* perceive the selected stimulus, namely that attention changes the phenomenological appearance of the percept. As a straightforward example of how attention would change the way we "see" the stimuli, in their study the authors depicted (see Fig. 4 of the Carrasco et al. study) three Gabors at different levels of contrast, in which the *visible* difference between the lowest (e.g., 16%) and the highest (e.g., 28%) levels corresponds to the experimentally measured change in contrast as a function of attention. Does attention also alter the phenomenological experience of motion speed? As we pointed out, in Experiment 1 the difference in speed caused by attention was smaller than the *JND*, a result that seemed to indicate that participants perceived the attended Gabor as moving faster without actually being aware of such a difference in speed. To directly test whether the increase in perceived speed caused by attention corresponded to a real phenomenological change, or was only due to a change in visual performance without awareness (Merikle et al., 2001), we conducted two experiments in which participants were asked to detect a difference in speed that was equal to (or a bit larger than) the magnitude of the difference caused by attention in Experiment 1. Specifically, in Experiment 5a participants' task was to decide whether the two Gabors moved at the same or different speed, but they were not able to detect any speed difference (d' was not different from zero). However, when in Experiment 5b participants were forced to decide which Gabor moved faster, despite reporting that they denied having seen any difference in speed, their visual performance was not at chance, as d' was significantly different from zero. This pattern of results is consistent with the possibility that the boost in the perceived speed documented in Experiment 1 occurred despite a lack of change in visual awareness. In other words, attention changed the performance of the visual system with regards to speed perception without altering the phenomenological appearance of the attended Gabor's speed. This conclusion is in agreement with the view according to which stimuli (and their properties) can be perceived even when there is no awareness of perceiving (Merikle et al., 2001). Also, the present findings can be considered as an example of a dissociation between visual performance and visual awareness. There are several cases in which the human being exhibits a dissociation (Merikle et al., 2001), but perhaps one of the most striking example is provided by the phenomenon of Blindsight, a neuropsychological disorder in which robust (albeit limited) visual performances remain despite a lack of awareness (e.g., Stoerig & Cowey, 1997). Indeed, despite a lesion to visual cortex, which causes "blindness" of the contralateral visual field, blindsight patients exhibit good visual performance (i.e. above chance) when they have to judge certain properties (e.g., direction of motion) of visual events in their blind field. In a sense, according to the results of Experiments 5a and 5b, participants might have behaved liked blindsight subjects, as they denied being aware of any difference in speed, but they guessed above chance which Gabor moved faster when forced to do so. In the same vein, perhaps they were not aware of the change in motion speed caused by attention (Experiment 1).

Because our findings have shown that attention alters the (implicit) perception of motion speed without changing its phenomenological appearance, one may wonder why attention would alter actual appearance in the case of perceived contrast (Carrasco et al., 2004) and spatial frequency (Gobell & Carrasco, 2005). To this aim we would like to point out that although the picture depicted in the Carrasco et al. study showing the effect of attention on contrast seems to provide compelling evidence of a change in visual appearance, there are reasons to suspect that the difference participants might have experienced was not as large as is apparent in the figure. First, one should note that appreciating the difference in contrast between stimuli on a printed figure without any time constraints might be quite different from the situation in which the same stimuli are presented peripherally on a computer screen for 40 ms. Second, if one tries to coarsely estimate from the figures the *JND* in the Carrasco et al. (2004) and Gobell and Carrasco (2005) experiments, it seems to be larger than the differences between the attention conditions.[1] So, although the results reported by Carrasco and her colleagues are of high interest, perhaps a more straightforward test of any possible change in the phenomenological appearance of the stimuli would require an experiment in which participants are directly asked to report if they see any difference between the stimuli when the difference in contrast or spatial frequency is equal to the estimated effect produced by attention (see Experiment 5a of the present study).

One may wonder why attention increases the perceived speed of moving objects rather than slow it down. As far as static visual properties are concerned, Gobell and Carrasco (2005) have proposed that attention increases, for example, the sensitivity of those spatial filters involved in the stimulus analysis, thus altering the perceived spatial frequency of the attended object as compared to the less attended one. Motion itself can be conceived as a structure of events that change in space and time with a certain frequency (Palmer, 1999), and indeed Adelson and Berger (1985) have proposed the existence of spatial-temporal frequency based filters for motion analysis. Interestingly, such motion filters can be tuned to different speeds of motion, so that one can hypothesize that attention might increase the perceived speed of a moving stimulus by shifting the sensitivity of the filters to a higher speed (a mechanism similar to the one proposed by Gobell and Carrasco, 2005, for spatial frequency).

In conclusion, the present study presents the first evidence that attention directly modulates the perceived motion speed of moving stimuli, and specifically, attention makes the brain believe that attended moving stimuli move faster.

[1] We thank an anonymous reviewer for having drawn our attention to this relevant issue about the results of Experiment 1 of the present study.

Acknowledgments

The authors thank David Burr, two anonymous reviewers and the members of the Cognitive Neuropsychology Laboratory at Harvard for their comments on earlier drafts of this paper. We also thank Christian Valt for his help in data collection.

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