On altering motion perception via working memory-based attention shifts

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Transient spatial attention has been shown to alter different stimulus properties, such as perceived contrast and speed of motion. Interestingly, recent studies seem to suggest that involuntary shifts of spatial attention can also occur on the basis of the contents of Working Memory (WM). According to the biased competition model of visual attention, stimuli in the visual field that match those currently maintained in working memory receive the highest attentional priority. In a series of five experiments we addressed whether WM-based attention shifts alter perception, and specifically speed of motion. We found that response times for target discrimination were shorter at the location where an object matching the one held in WM was presented, thus confirming WM-based attention shifts. In contrast, results from other experiments, in which a speed-discrimination task was used, failed to reveal any modulation of motion speed perception by the content of WM. At present these data suggest that WM-based attention operates at different (later) stages of visual analysis than transient attention.

Keywords: attention, motion perception, working memory


Introduction

Consistent evidence has recently accumulated showing that visual attention can alter perception. Attention increases perceived contrast (Carrasco, Ling, & Read, 2004), spatial frequency or gap size (Gobell & Carrasco, 2005), and color saturation (Fuller & Carrasco, 2006). In addition to changing static stimulus features, attention has been shown to alter the perception of dynamic stimulus properties, like perceived speed of motion (Turatto, Vescovi, & Valsecchi, 2007) and motion coherence (Liu, Fuller, & Carrasco, 2006). Exogenous or bottom-up shifts of attention take place when salient events, such as, for example, abrupt visual onsets, occur in the visual field (Jonides, 1981; Nakayama & Mackeben, 1989). On the contrary, endogenous or top-down control is achieved when attention is allocated according to the observers’ goals and intentions (e.g., Posner, 1980). To date, evidence that attention can alter perception comes from studies using paradigms that manipulated exogenous attention. Within the class of top-down mechanisms that are possibly involved in attentional control an important one is visual working memory (WM). WM refers to functional storage mechanism(s) that are devoted to temporarily maintaining information available to cognitive systems for further processing (Baddeley, 1986).

Visual working memory and attention

Possible functional links between WM and attention have long been studied in cognitive psychology and the neurosciences (Awh & Jonides, 2001). The relation between attention and WM has been explored along two main research lines: one has emphasized the pivotal role of spatial attention for the maintenance of information in WM (Awh, Jonides, & Reuter-Lorenz, 1998; Smyth & Scholey, 1994), while the other has mainly addressed whether the content of WM can affect the allocation of visual attention (Downing, 2000). The present study intended to ascertain whether WM-based attention shifts can alter perception, and specifically the perceived speed of motion.

Perhaps the most obvious way in which information stored in WM can interact with the deployment of visual attention is by keeping the target template active during visual search (Duncan & Humphreys, 1989). This relation is made explicit in the Desimone and Duncan (1995) biased-competition theory of visual attention. The model posits that the different objects (and their corresponding neural representations) compete for access to higher levels of processing in the visual system. Specifically, if two (or more) competing objects are simultaneously present, the object that eventually matches the content of WM (for example the search template) gains preferential access to
later stages of analysis. Single-cell recording studies have provided evidence consistent with this view. Among others, Chelazzi, Duncan, Miller, and Desimone (1998) showed, in macaque infero temporal (IT) cortex, that when the search display is presented the response of those neurons that code the irrelevant and unattended stimulus is suppressed. In addition, they also found that those IT neurons that maintained the target template active before the search display was presented responded more vigorously as compared to those that were preferentially tuned to the distractor.

The idea that WM could bias visual selection by involuntarily directing attention toward the information in the visual field that matches its content (even when task irrelevant) has recently received experimental support. Downing (2000) was among the first to demonstrate the “automatic” link between WM and attention. In this study, on each trial the observers were required to memorize a given face for a later recognition test. Then, two irrelevant-distractor faces, one on each side of fixation were briefly presented before a probe appeared on the screen. The observers’ task was to decide whether the probe was upright or upside-down rotated, with the probe appearing in a location previously occupied by one of the two distractor faces. The main finding was that response times (RTs) for probe discrimination were shorter when the probe position overlapped the distractor face matching that in WM. This pattern of results was interpreted as due to an involuntary shift of attention toward the irrelevant matching face.

Other studies have obtained consistent findings (but see, Woodman & Luck, 2007), showing involuntary shifts of attention to locations of the visual field containing the object stored in WM. This occurred both during complex visual search tasks (Soto, Heinke, Humphreys, & Blanco, 2005), and when the information held in WM matches that of an irrelevant distractor singleton (Olivers, Meijer, & Theeuwes, 2006; also see Pashler & Shiu, 1999). Furthermore, there is evidence that attention is engaged by a given stimulus even when it only partially matches the content of WM (Soto et al., 2005), or when it is linked to the object held in WM via associative links involving long-term memory (Moores, Laiti, & Chelazzi, 2003).

Previous studies (e.g., Carrasco et al., 2004). On the other hand, attention is a very general term that refers to different brain mechanisms through which the visual system prioritizes the analysis of information. So, for example, attention might facilitate visual analysis by altering the speed of information processing (Posner, 1980), by facilitating response selection (Eriksen & Eriksen, 1974), by enhancing perceptual sensitivity (Cameron, Tai, & Carrasco, 2002), or by acting at all of these levels (or a combination of them) together.

It is clear that WM-based attention shifts facilitate performance by reducing manual and oculomotor RTs (e.g., Olivers et al., 2006). However, it is not yet known as to whether this type of attention selection can also change visual perception at early levels of visual processing. In the following series of experiments we directly test this hypothesis.

Experiments 1, 2, and 3

In a previous study (Turatto, Vescovi et al., 2007) showed that motion perception is altered by exogenous attention. We presented two Gabor patches (vertical sinusoidal achromatic gratings enveloped by a Gaussian filter), one on each side of fixation, and each one randomly drifted leftward or rightward. One Gabor (the standard) moved at a fixed speed, while the other (the test) could move at the same speed, slower or faster. Before the Gabors’ appearance, a peripheral visual onset was briefly presented to the left or to the right of fixation to trigger a shift of visual attention to a location subsequently occupied by one of the two Gabors. Then, observers were asked to report which Gabor appeared to have moved faster (or slower). Results showed that, as compared to a control condition in which attention remained at fixation, the speed of the cued Gabor was overestimated, whereas that of the uncued Gabor was underestimated. In agreement with previous studies by Carrasco and her collaborators, we provided converging evidence that exogenous attention shifts can alter perception, and specifically motion speed. Here, by means of a very similar paradigm, we addressed whether WM-based attention shifts can also alter, and to what extent, motion perception. The possibility to find such a modulation in Experiments 1, 2, and 3 rests on three assumptions. The first is that even a partial match between the item stored in WM and that appearing on the display is sufficient to trigger a shift of attention. So, for example, in Experiment 1 we asked participants to memorize the orientation of the sample static Gabor, while its color could or could not match that of the test moving Gabor subsequently presented. The second assumption is that if attention were shifted to the test Gabor because it matches the color of the sample
Gabor, the effect of attention extended also to other dimensions of the test Gabor (say speed). The third assumption is that when there is a match between a visual item and that held in WM, attention is shifted to the location of the former. The first two assumptions seem to be justified on the basis of what Luck and Vogel (1997) have found, namely that objects are stored in WM as discrete perceptual units. So, when a specific characteristic of a given item is held in WM, all the characteristics defining the item are retained in the corresponding WM representation. The third is empirically motivated: There is ample evidence documenting involuntary shifts of attention to locations of the visual field containing the object stored in WM (e.g., Downing, 2000) or toward objects that even partially match the content of WM (Soto et al., 2005).

Method

Observers

All observers had normal or corrected-to-normal visual acuity, reported having no difficulties with color vision, and were naïve as to the purpose of the study. All were students at the University of Trento, and participated in exchange for course credits, or were paid 6 Euros for their participation. Eight students participated in Experiment 1 (mean age = 23 years), 6 in Experiment 2 (mean age = 27 years), and 8 in Experiment 3 (mean age = 26 years).

Observers were different among the different experiments. Each observer completed one experiment.

Apparatus

The apparatus was identical in all the experiments of the present study. Participants sat approximately 60 cm in front of an Iiyama CRT 1900 monitor (1024 × 768, 150 Hz). 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. Head movements were restrained by using a cheekbone and chin rest device.

Stimuli

Experiments 1 and 2

The stimuli were presented over a black background (0.5 cd/m²). In the speed-discrimination task the stimuli consisted of two colored Gabors (vertical sinusoidal chromatic gratings enveloped by a Gaussian filter; 3° × 3°). Each Gabor was made of black gratings combined with either red (x = 0.615, y = 0.350, CIE coordinates), blue (x = 0.160, y = 0.116), green, (x = 0.304, y = 0.595), yellow (x = 0.464, y = 0.464), or gray (x = 0.277, y = 0.315) gratings. The five colors had approximately the same luminance (4.80 cd/m²). Each Gabor appeared over a circle (4° of visual angle in diameter) whose color was the average color of the Gabor (see Figure 1). The Gabor’s motion was achieved by independently shifting the black and colored gratings leftward or rightward. One of the two Gabors (the standard) moved at a fixed speed (4.29°/s), while 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 speed values were the same as those used in Turatto, Vescovi et al.’s (2007) study. The contrast of the Gabors was 60%. In the memory task the “sample” and “probe” Gabors were stationary. In Experiment 1 they could have one of 8 possible orientations with respect to the vertical axis (20, 40, 60, 80, 100, 120, 140, or 160°), whereas in Experiment 2 they were always vertical (0°). The fixation point consisted of a small white disk subtending 0.2° of visual angle.

Experiment 3

Everything was the same as in Experiment 2 except that the sample Gabor moved at a fixed speed of 4.29°/s.

Procedure

Experiment 1

Each trial started with the presentation of the “sample” Gabor at the center of the screen for 1000 ms. Participants were instructed to memorize the orientation of this Gabor for a later match-to-sample task. After 500 ms had elapsed, the fixation point appeared at the center of the screen, and remained visible for 2500 ms. Then the two Gabors were presented for 200 ms, 4° to the left and right of fixation. Once the Gabors disappeared, a question mark replaced the fixation point, signaling participants to report the direction of movement of the Gabor that they judged to have moved faster. In principle, to address the effect of a WM-based shifts of attention on speed perception, we may have asked participants simply to report which Gabor moved faster. However, to minimize the possibility of a response bias (i.e., of a tendency to report the Gabor that matched the one in WM), and to be consistent with the task adopted in our previous study (Turatto, Vescovi et al., 2007), we adopted the procedure suggested by Carrasco et al. (2004). Here, observers performed a direction of motion discrimination task contingent on the stimulus that appeared to move faster. This experimental design emphasized to observers the direction judgment, when in fact we were interested in their speed judgments.

Hence, participants performed a 2 by 2 alternative forced-choice task: if the left Gabor was perceived as being faster, they responded with their left hand by pressing the “W” key (middle finger) or the “E” 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 “I” key (index finger) or the “O” key (middle finger) depending on whether motion was leftward or rightward, respectively. 500 ms after the response was delivered, the probe Gabor of the memory task appeared at the center of the screen, and remained visible until participants responded by pressing the “Q” key (ring finger, left hand) if the probe matched the sample (in terms of orientation) and the “P” key (ring finger, right hand) if it did not. A 1500-ms blank interval followed before the next trial began (see Figure 1 for a schematic representation of the trial events of Experiments 1, 2, and 3).

Experiment 2

Everything was the same as in Experiment 1 except that participants were required to memorize the color of the sample, and to decide whether the probe Gabor did or did not have the same color.

Experiment 3

Experiment 3 was the same as Experiment 2, with the exception that the sample Gabor was presented in motion as were the test and standard Gabors.

Design

The design was the same in all experiments. In the speed-discrimination task participants were submitted to a $3 \times 7$ factorial design, in which the factors were congruency (on congruent trials the color of the sample Gabor matched the color of the test Gabor; on incongruent trials the color of the sample Gabor matched the color of the standard Gabor; on neutral trials the color of the sample Gabor neither matched that of the test nor that of the standard) and speed of the test Gabor. Each cell of the design had 24 trials, divided into 3 blocks, for a total of 504 trials per participant.

In the memory task the sample and the probe Gabor matched in terms of the relevant feature (orientation in Experiment 1, color in Experiments 2 and 3) on 50% of the trials.

Results and discussion

Experiment 1

Participants’ accuracy in the memory task was 80%. In this and the following experiments for the analysis of the speed-discrimination task we considered only those trials in which participants were accurate in the memory task, and calculated the proportion of trials in which the test Gabor was judged to move faster than the standard Gabor as a function of whether the color of the sample Gabor matched that of the test, the standard, or none of them (control condition).
Results are depicted in Figure 2 (here, and in the following experiments, the curve was generated by a Gaussian fit of the corresponding data. The horizontal line intersecting the curves indicates the Point of Subjective Equivalence, PSE). The curves are Gaussian fits of the data.

Results are depicted in Figure 2 (here, and in the following experiments, the curve was generated by a Gaussian fit of the corresponding data. The horizontal line intersecting the curves indicates the Point of Subjective Equivalence, PSE). As is evident the three psychometric functions overlapped almost completely, and this was confirmed by an ANOVA which revealed only a significant main effect of test speed $F(6,42) = 105.536, p < .0001$, 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 than the standard, while it was minimal at the PSE. Neither the main effect of congruency $F(2,10) = .188, p = .832$, nor the interaction between the two factors $F(12,60) = .925, p = .528$, was significant.

However, in order to rule this possibility out, in Experiment 2 participants were explicitly asked to remember the color of the sample Gabor.

**Experiment 2**

Participants’ accuracy in the memory task was 95%.

Results of the speed-discrimination task are depicted in Figure 3. As in Experiment 1 the three psychometric functions overlapped, as confirmed by an ANOVA which revealed only a significant main effect of test speed $F(6,30) = 46.344, p < .0001$. Neither the main effect of congruency $F(2,10) = .188, p = .832$, nor the interaction between the two factors $F(12,60) = .925, p = .528$, was significant.

This result cannot be accounted for by a mismatch between the information stored in WM (i.e., orientation) and that related to either the test or the standard (i.e., color). However, one might further note that although the test and standard had the same color as the sample on congruent and incongruent trials respectively, the latter were stationary whereas the former was in motion. Hence, it could be feasible that for the visual system a red stationary Gabor and a red moving one might not be one and the same thing, and therefore no matching between the two via WM would have taken place. If this were the case no shift of attention toward the Gabor that had the same color as the one held in WM would have been triggered, and therefore no change in perception would occur. To address this possibility, in Experiment 3 the sample Gabor was presented in motion.

**Experiment 3**

Participants’ accuracy in the memory task was 97%.

Figure 2. Results of Experiment 1. 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 congruency conditions. The downward-pointing arrows indicate the point of subjective equivalence (PSE). The curves are Gaussian fits of the data.

Figure 3. Results of Experiment 2. No changes in the PSE as a function of condition emerged.
Results of the speed-discrimination task are depicted in Figure 4. As in previous experiments the three psychometric functions overlapped, as confirmed by an ANOVA, where the only significant main effect was test speed $F(6,42) = 15.497, p < .0001$. Again, neither effect of congruency $F(2,14) = .211, p = .812$, nor the interaction $F(12,84) = 1.536, p = .127$, were significant.

Although one must always be very cautious in drawing conclusions from null effects, so far the present set of experiments, which all produced consistent findings, suggests that working memory-driven attention shifts do not alter motion perception. However, before we can accept this conclusion two further crucial controls need to be carried out. Indeed, two viable reasons for why we did not document a change in perception in Experiments 1, 2, and 3 are the following. First, it could be the case that for some unknown reason no change in motion perception can be obtained with colored moving Gabors, even if transient attention were used (see Turatto, Vescovi et al., 2007). Second, the paradigm we used could have been ineffective in summoning attention toward the object in the visual field matching the one held in WM. These concerns were addressed in Experiment 4.

Experiment 4

The present experiment consisted of two separate sessions, counterbalanced across participants. In one session we used the paradigm adopted by Turatto, Vescovi et al. (2007), with the exception that we used colored instead of achromatic Gabors. In this paradigm attention allocation is elicited by means of peripheral visual onsets, a condition that has been shown to alter stimulus perception (e.g., Carrasco et al., 2004; Turatto, Vescovi et al., 2007).

In the other session, we directly evaluated whether the Gabor that matches the one held in WM can trigger a shift of attention toward the corresponding location. To this aim we engaged participants in a visual search task, in which they had to discriminate as quickly as possible the orientation (left vs. right) of a target letter T. The target T and the distractor L appeared at the center of two horizontally-arranged irrelevant Gabors (see Figure 6). We then manipulated the spatial correspondence between the target location and the position of the irrelevant Gabor matching the one held WM: on congruent trials the two stimuli coincided; on incongruent trials the target T appeared on the opposite Gabor; on neutral trials none of the two Gabors matched that maintained in WM.

Method

Observers

All observers had normal or corrected-to-normal visual acuity, reported having no color-vision defects, and were naive as to the purpose of the study. All were students at the University of Trento, and participated in exchange for course credits, or were paid 6 Euros for their participation. Twelve students participated in the experiment (mean age = 25 years).

Stimuli

In the speed-discrimination task the speed and the colors of the Gabors were the same as in Experiment 3. The peripheral cue consisted of a small white dot appearing just above one of the two Gabors (see Turatto, Vescovi et al., 2007).

In the memory task the target consisted of the letter T (0.6°) presented 90° clockwise or counterclockwise rotated and superimposed in the center of one of the two Gabors. The distractor consisted of the letter L (0.6°), rotated to the left or right, and appearing over the Gabor opposite to the one with the target. The color of the test and probe Gabors were those used in previous experiments.

Procedure

In the speed-discrimination task the procedure was identical to that already described in Turatto, Vescovi et al. (2007) and depicted in Figure 5.

In the memory task the procedure was identical to that used in the corresponding task of Experiment 2 (i.e., the Gabors were stationary), with the following exceptions. When the two concomitant horizontally-arranged Gabors appeared on the screen, one contained the letter T and the other the letter L. The Gabors and the letters remained visible for 200 ms. Participants had to respond as quickly as possible to the orientation of the T by pressing one key.
for “right” and a different one for “left”. The display was then replaced by the probe Gabor. Then the observers had to decide whether the probe did or did not have the same color as the sample Gabor (see Figure 6).

**Design**

A $2 \times 7$ factorial design was used in the speed-discrimination task. In order to reduce the overall duration of the experiment, which now consisted of two tasks, in the speeded-discrimination task we used only the test-cue and neutral condition. Hence participants were submitted to a $2 \times 7$ factorial design, in which the factors were cue (test vs. neutral) and speed (7 levels, see previous experiments). Each cell of the design had 24 trials, divided into 3 blocks, for a total of 336 trials per participant.

In the memory task, the crucial factor was congruency: we presented 48 congruent trials, 48 incongruent trials,
and 48 neutral trials. On half of the trials the probe Gabor matched the sample Gabors, while on the remaining trials it did not.

Results and discussion

Speed-discrimination task

Results are depicted in Figure 7. As is evident, the curve of the test-cue condition shifted to the left of the control condition, showing that the peripheral cue was effective in altering the PSE, namely the perceived speed of the attended Gabor. This was confirmed by an ANOVA, where the main effect of cue $F(1,11) = 15.335, p < .002$, speed $F(6,66) = 137.665, p < .0001$, and their interaction $F(6,66) = 4.560, p < .001$, were significant. The present findings confirm those of Turatto, Vescovi et al. (2007), showing that attention changes the perceived speed of both achromatic and colored moving Gabors. Therefore, the reason why we did not find evidence of attention modulation in the Experiments 1, 2, and 3 cannot be accounted for by the fact that we used colored Gabors.

Memory task

Participants’ accuracy in the memory task was 86%. RTs were entered into a repeated measures ANOVA with congruency as a factor. There was a main effect of congruency, $F(2,22) = 9.020, p < .001$. Participants were faster on congruent trials ($M = 541$ ms; $SE 21$) than on neutral trials ($M = 581$ ms; $SE 29$); participants were also slower on incongruent trials ($M = 612$ ms; $SE 27$) as compared to neutral trials. This pattern of results confirmed that the information held in WM summoned attention, thus speeding up target discrimination when it appeared in the corresponding location. These findings are in agreement with those of several recent studies (e.g., Downing, 2000; Soto et al., 2005) showing that attention is involuntarily directed toward the stimulus that matches the content of WM. In addition, this result undermines the possibility that in previous experiments we failed to report a change in perception because no shifts of attention took place according to the contents of WM.

Note that the present findings, together with those from other studies (e.g., Downing, 2000; Soto et al., 2005) are informative about the mechanisms mediating memory-based attentional selection. Indeed, one could hypothesize that the facilitatory effects are due to a shift of spatial attention to the location occupied by a stimulus whose features match the content of WM. However, the fact that in the present experiment we found an RT advantage in target discrimination for a target (the letter T) that did not share any feature with the object held in WM (the colored Gabor), strongly suggests that the facilitatory effect was mediated by a spatial shift of attention that prioritized the analysis at the selected location.

The overall picture emerging from the present set of experiments seems to indicate that although an object matching the content of WM indeed attracts attention, thus speeding up the discrimination of the information occurring at the corresponding location, the perceptual properties (here speed) of the memory-based attended object are not altered in the same way they are altered by a peripheral spatial cue. However, before accepting this conclusion, it is worth considering another important factor that might have prevented us from observing effects of WM-based attention shifts on perceived motion perception. In the next experiment we explored this further issue.

Experiments 5a and 5b

In previous experiments showing that attention altered contrast and motion perception (e.g., Carrasco et al., 2004; Turatto, Vescovi et al., 2007), and in the speed-discrimination task of Experiment 4, the paradigm adopted consisted of a peripheral cue presented before the occurrence of the two Gabors. The cue was shown approximately 150 ms in advanced, in order to give enough time to the automatic orienting of attention to take place (Nakayama & Mackeben, 1989), thus producing its maximal beneficial effect on performance. On the
contrary, in the paradigm that we have adopted so far, the
object that is supposed to trigger a shift of attention
(acting like a cue) is also one of the two objects upon
which the perceptual discrimination has to be made. In
other words, there was a perfect temporal overlap between
the cue information and the target-object information,
which would correspond to a 0-ms stimulus onset
asynchrony (SOA) in the peripheral-cue paradigm.

Hence, it may be argued that the reason why we did not
find evidence that motion perception was altered by WM-
driven attention allocation is because the paradigm did not
allow time for this type of attention allocation to occur
before the appearance of the test and standard Gabors.
Since it is not yet clear whether the shift of attention
caused by the content of WM is more automatic or
strategic in nature, as a first step in Experiment 5a we
decided to use an SOA that was a reasonable compromise
between the classic time-course of the two types of
orienting mechanisms. Thus, a 500-ms SOA was used
between the WM-distractor and the occurrence of the
Gabor. In Experiment 5b we specifically addressed the
possibility that WM-based attention shifts were more like
an automatic-type of orienting, thus having a brief time
course. To this aim a 150-ms SOA was used.

Method

Observers

All observers had normal or corrected-to-normal visual
acuity, reported having no color-vision defects, and were
naive as to the purpose of the study. They were students at
the University of Trento, and participated in exchange for
course credits, or were paid 6 Euros for their participation.
Sixteen and ten students, respectively, participated in
Experiment 5a (mean age = 24 years) and 5b (mean age =
22 years).

Stimuli

The speeds and colors of the Gabors were the same as in
Experiment 3.

In the memory task, the sample object, the distractor
object, and the probe object could be one of four possible
outlined shapes (square, circle, diamond, or hexagon)
randomly associated with one of four different colors (red,
green, blue, and yellow).

Procedure

Each trial started with the presentation of the sample
figure at the center of the screen for 1000 ms, and
participants were instructed to memorize its shape and
color for later comparison. After a 500-ms interval had
elapsed, the fixation point appeared at the center of the
screen, and remained visible for 1000 ms. Then the two
distractor figures were presented 4° to the left and right
of fixation. After a 500-ms (Experiment 5a) or a 150-ms
(Experiment 5b) SOA the two Gabors appeared inside
the distractor figures for 200 ms. A question mark then
replaced the fixation point, signaling participants to
report the direction of movement of the Gabor that they
judged to have moved faster (also see previous experi-
ments). 500 ms after the response was delivered, the
probe figure of the memory task appeared at the center
of the screen, and remained visible until participants
responded as to whether it matched the sample or not. A
1500-ms blank interval followed before the next trial
began (see Figure 8 for a schematic representation of the
trial events).

Design

A 3 × 7 factorial design was used both in Experiments
5a and 5b, in which the factors were congruency (test,
neutral and standard) and speed (7 levels, see previous
experiments). Each cell of the design had 24 trials,
divided into 3 blocks, for a total of 504 trials per
participant.

In the memory task, the crucial factor was congruency:
we presented 168 congruent trials, 168 incongruent trials,
and 168 neutral trials. On half of the trials the probe
figure matched the sample figure, while on the remaining
it did not.

Results and discussion

Experiment 5a

Participants’ accuracy in the memory task was 81%. One
participant was removed from the data set because he
systematically responded by indicating the Gabor coincid-
ing with the memorized figure as being the fastest. Results
from the remaining 15 participants are depicted in Figure 9,
where the three curves clearly overlapped showing no
effect of the content of WM on motion perception. An
ANOVA confirmed these observations, as speed was the
only significant factor $F(6,84) = 451.402, p < .0001$,
whereas the factor congruency $F(2,28) = .927, p = .407$,
and the interaction $F(12,168) = .892, p = .556$, were not
significant. These findings mirrored those of Experiments 1,
2, and 3, showing that no changes in speed perception
of the Gabor appearing at the location of the object
currently held in WM was observed.

Experiment 5b

Participants’ accuracy in the memory task was 80.4%.
The results of the speed discrimination task are depicted
in Figure 10, where the three curves clearly overlapped
showing no effect of the content of WM on motion
perception. An ANOVA confirmed these observations, as
speed was the only significant factor $F(6,66) = 115.910$, $p < .0001$, whereas the factor congruency $F(2,22) = .166$, $p = .848$, and the interaction $F(12,132) = .481$, $p = .923$, were not significant. These findings mirrored those of Experiment 5a showing that no changes in speed perception of the Gabor appearing at the location of the object currently held in WM was observed.

**General discussion**

A close connection between WM and attention is both suggested by intuition (e.g., we know that we have to pay attention to the name of the person we are introduced to in order to remember it later) and documented by experimental

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Figure 8. Sequence of trial events in Experiments 5a and 5b. Stimuli are not drawn to scale. The horizontal white arrows illustrating some possible directions of motion were not shown in the display.

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Figure 9. Results of Experiment 5a. No changes in the PSE as a function of condition emerged when a 500-ms SOA was used.

Figure 10. Results of Experiment 5b. No changes in the PSE as a function of condition emerged when a 150-ms SOA was used.
observations (Awh & Jonides, 2001; Miller & Cohen, 2001). In particular, while it is relatively undisputed that attention plays a central role in maintaining information in WM (Awh et al., 1998; Smyth & Scholey, 1994), whether WM itself can determine the allocation of attention seems to be a more controversial issue. This second possibility stems more or less implicitly from many models of visual attention when they posit the presence of top-down control mechanisms, in which, for instance, the identity of the target is held during visual search (e.g., Bundesen, 1990; Duncan & Humphreys, 1989; Treisman & Sato, 1990; Wolfe, 1994). In this sense, the relation is made clear in the Desimone and Duncan (1995) biased competition theory of visual attention. The theory holds that sensory inputs compete in the visual system for neural representations, with those matching the current content of WM being advantaged over those that do not. Accordingly, recent evidence has shown that items matching the content of WM trigger an involuntary shift of attention toward the corresponding location (Downing, 2000; Olivers et al., 2006; Pashler & Shiu, 1999; Soto et al., 2005; but see Woodman & Luck, 2007). If this is the case, and given that there is now ample documentation that attention alters perception (e.g., Carrasco et al., 2004), one might expect that a WM-based attention allocation should also change visual perception.

As far as the perception of motion speed is concerned, we directly tested this hypothesis in the present set of experiments. Although prudence is always necessary in drawing conclusions from null results, the findings of this series of experiments consistently indicate that motion perception is not altered by WM-based shifts of attention, at least under the experimental conditions tested here. Critically, the conditions are standard for observing effects of attention due to WM. This lack of modulation of motion perception was found when the content of WM was incidentally related to the information in the display (Experiment 1), was exactly the same but appeared concurrently and coincided with the moving Gabors (Experiments 2 and 3), or was presented 150 or 500 ms in advanced and did not coincide with the moving Gabors (Experiments 5a and 5b). One obvious reason that might explain our negative findings would be that the paradigm we have employed was not adequate to a) elicit a WM-based shift of attention; b) alter speed perception when colored Gabors are used. However, these explanations can be ruled out on the basis of the results of Experiment 4, in which we showed that a change in motion speed emerged when attention was shifted using a peripheral visual transient (Turatto, Vescovi et al., 2007), and that shorter RTs for the target discrimination were found at the location of the object matching the one held in WM. Crucially, this latter finding corroborates those from other studies (e.g., Downing, 2000; Olivers et al., 2006; Pashler & Shiu, 1999; Soto et al., 2005), while at the same time reassures us that the paradigm we adopted was in general adequate for eliciting a shift of attention.

The results of the speed-discrimination task may seem more in accordance with the findings of Woodman and Luck (2007), who, overall, did not find evidence for involuntary WM-based shifts of attention. Yet, such negative outcomes were observed in visual search tasks during which the observers were informed that the object matching the one held in WM was never the target (Experiments 1 to 4). By contrast, when the content of WM could occasionally match the target (Experiment 5), the authors found an RT pattern that, albeit non-significant, was in agreement with the hypothesis that an involuntary shift of attention, according to the contents of WM occurred (e.g., Downing, 2000; Soto et al., 2005). Results from Experiment 4 of the present study also provided RT findings consistent with this view. Thus, despite the fact that we did not observe a modulation of speed perception, we are more sympathetic with the hypothesis that when competing sensory inputs are presented attention is preferentially allocated to those matching the content of WM.

Our negative findings might seem in disagreement with those reported by Awh et al. (1998), who found that visual processing at memorized locations was more efficient than at non-memorized locations. Yet, the difference between the two studies is more apparent than real. First of all, one should note that in Awh and colleagues’ study attention was voluntarily allocated to a given position to refresh the corresponding spatial information in WM. By contrast, in the present study we used the content of WM to elicit an involuntary shift of attention. Obviously the two mechanisms might not be one and the same thing. Second, and more importantly, Awh and colleagues reported improved perception at the memorized location in terms of RTs, which is exactly what we found in the T/L task of Experiment 4.

How then can the lack of modulation of motion perception found in the present set of experiments be explained? We would suggest two different possibilities. The first possibility would assume that when attention is shifted as a consequence of a low level visual change such as a peripheral flash (e.g., Carrasco et al., 2004; Turatto, Vescovi et al. 2007) attention modulates early stages of visual processing, so that contrast and motion can be altered. By contrast, when the shift of attention is controlled by more strategic top-down factors like the content of WM, the modulation is achieved only at later stages of processing such as, for instance, the level of response selection (Ekrenk & Eriksen, 1974).

The second possibility would call into question the distinction between global and local visual processing, or in other words, between distributed and focused attention (Nakayama, 1990). As Bravo and Nakayama (1992) have elegantly showed, there are visual tasks that can be performed in a distributed attention mode, namely without the need to shift and narrow the focus of attention to a given location. This is the case, for example, when simple feature detection is required, so that the visual system can
operate on a broader attention scale to simply detect a discontinuity in the visual field. However, if the task requires details of the singleton to be discriminated, like for instance the side on which its shape is truncated, then focused attention needs to be shifted to the corresponding location, as testified by a change in RTs as a function of display numerosity (Bravo & Nakayama, 1992) and of oculomotor activity (Turatto, Valsecchi, Tamè, & Betta, 2007). Within this perspective one could argue that in the T/L task of Experiment 4, as well as in other tasks in which evidence for an involuntary WM-based shift of attention has been documented, target discrimination required focused attention to be shifted to a given position in the display (e.g., Downing, 2000; Olivers et al., 2006; Soto et al., 2005). By contrast, in the speed-discrimination mode, when the attention system is set to operate in a focused distributed attention mode. Hence, one might hypothesize that the content of WM can trigger a shift of attention only when the attention system is set to operate in a focused mode.

Conclusions

The present set of experiments was devised in order to establish whether WM-based attention shifts caused by task-irrelevant information can alter motion perception. Despite the fact that exogenous attention increases the perceived speed of motion, at present, our results suggest that this is not the case when attention is allocated according to the content of WM. Further studies will be necessary to corroborate the present outcomes, or to delineate the conditions under which a change in perception due to WM-based attention shifts, if any, can be observed.

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