Exp Brain Res (2005)
DOI 10.1007/s00221-005-0056-4

RESEARCH ARTICLE

Massimo Turatto · Bruce Bridgeman

Change perception using visual transients: object substitution and deletion

Received: 11 January 2005 / Accepted: 29 April 2005

Abstract In three experiments we studied change detection and identification when no extraneous transients were present in the image at the time of change. Each image consisted of 12 different objects, sorted by color into three different levels of probability of change. In Experiment 1, change of one object was detected and identified frequently in objects having the highest probability of change (central interest), which we hypothesize were mainly visited by attention. Changes in other objects with a lower probability of change (marginal interest), however, although detected efficiently were unlikely to be identified. Identification improved for less attended objects if the changed stimulus simply disappeared, allowing visual persistence to hold information about the object until attention could be shifted to it (Experiment 2). Contrary to previous findings showing that response times (RTs) for luminance change detection in a multi-element display are not altered by attention, we found changes in objects of central interest to be detected faster than in objects of marginal interest when objects' identity was to be held in working memory. However, no differences in RTs emerged in the same change detection task when objects' identity was not stored in working memory (Experiment 3).

Keywords Attention · Visual transients · Change perception · Change blindness · Working memory

M. Turatto (✉)
Department of Cognitive Science and Education,
University of Trento,
Via Matteo del Ben, 5, 38068 Rovereto, Italy
E-mail: massimo.turatto@unitn.it
Tel.: +39-464-483529
Fax: +39-464-483554

B. Bridgeman
University of California, Santa Cruz, CA, USA

Introduction

For many common human activities, such as driving, it is important to rapidly note changes in the visual environment. It is therefore of obvious interest to study how the human visual system processes and handles information concerning change (Rensink 2002). Before becoming an issue of investigation itself in the last decade, change perception has been widely employed since the 1970s to investigate the functional organization of the visual system, with a particular reference to 'peripheral' and 'central' visual memory systems (e.g., Singer and Phillips 1974). More recently, however, research has concentrated on a phenomenon that is the counterpart of change perception, namely change blindness. Change blindness refers to the fact that human observers are dramatically poor at perceiving even striking changes when the change occurs along with other visual events or disturbances interrupting visual continuity (Rensink 2002; Simons and Levin 1997). For example, in one of the first change blindness studies, McConkie and Currie (1996); also see (Bridgeman et al. 1975; Grimes 1996) showed that observers were virtually blind even to large changes in real world images when they took place during saccadic eye movements.

Remarkably, however, people can remain blind to changes regardless of whether they take place during eye movements (Simons and Levin 1997). Indeed, a change can remain unnoticed if it takes place during a brief blank of the image (Rensink et al. 1997), a film cut (Levin and Simons 1997), a polarity reversal of the image (Turatto et al. 2003), when other irrelevant spots are suddenly displayed on the screen at the time of change (O'Regan et al. 1999), or if the change coincides with an eye blink (O'Regan et al. 2000).

For a better understanding of the cognitive mechanisms underlying change blindness it would be useful to clarify the physiological and cognitive processes subserving successful change perception without global transients. In the present paper we avoid conditions in which there are sudden ‘extraneous’ visual events in the scene at the time of change. Hence, the only visual transient (explanations follows) is that caused by the change itself. In addition, in many change blindness studies, in which the visual transient accompanying the change is absent or useless to perceive the change, the term ‘change detection’ refers to the fact that participants consciously report the presence of change (e.g., Henderson and Hollingworth 1999; Rensink et al. 1997; McConkie and Currie 1996; O’Regan et al. 1999). Although there are theoretical and empirical reasons to believe that detecting and identifying a change in a typical change blindness tasks might not be the same thing (Beck and Levin 2003; Watanabe 2003), often the term *change detection* “... denotes not only detection proper (i.e., the observer reporting the existence of the change), but also identification (reporting what the change is) and localization (reporting where the change is).” (Rensink 2002, p. 246). Actually, some change blindness studies have reported no difference in performance when change detection and identification have been compared (e.g., Mondy and Coltheart 2000), which seems to justify the use of the general term change detection to refer to the perception of change (but see Beck and Levin 2003; Brawn et al. 1999).

There are even stronger reasons to refer to change detection and identification as two distinct processes when change perception is evaluated and when no extraneous transients are present at the time the change takes place. Indeed, change detection would be the mere conscious registration that something has changed without any knowledge about the nature of the change. Change identification, instead, would refer to the ability to identify what has been changed. Finally, we define the term ‘visual transient’ as any sudden change in the luminance pattern at the retinal level that is sufficiently large to generate a transient burst of neural activity in those cortical and subcortical areas responsible for attentional and oculomotor orienting (Breitmeyer and Ganz 1976; Corbetta and Shulman 2002; Singer and Phillips 1974). This covert and/or overt orienting reflex is quite powerful; visual transients, unless actively counteracted (Theeuwes 1991; Warner et al. 1990), usually attract attention (and the eyes) to the corresponding spatial location (e.g., Jonides 1981).

Mechanisms of change perception without extraneous transients

When moving in the environment, visual search behavior is affected by the way attention is allocated in the visual field. Broadly speaking two main classes of factors, endogenous and exogenous, are thought to govern attentional allocation (Yantis 2000). Endogenous attention is deployed according to goal-directed or top-down factors, which represent our goals and intentions. In contrast, when attention is captured by a salient but irrelevant element, it is said to be directed in a stimulus-driven manner or by bottom-up factors (Turatto and Galfano 2000, 2001). Once bottom-up and top-down factors are combined together in the ‘activation map’, the result is a sort of ‘priority list’ that attention will follow in being deployed across items in the scene (Wolfe 1994). Hence, elements that turn out to be particularly salient and/or behaviorally relevant (i.e., similar to the target of the current search) will be ranked at the top of the list. These high-priority items will be the first visited by attention, and, when scene exploration requires multiple attention scans, those items are likely to be scanned first and with higher frequency. Since attention is important to consolidate and transfer information from a volatile sensory or iconic representation into short-term memory, an important consequence is that the more an item is visited by attention the more likely that its properties will be stored in a relatively stable manner, whereas items that are not attended are subject to fast decay and forgetting (Wolfe 1999). Only those items that are moved to this more durable storage become part of our conscious visual representation and can be used for comparisons with previous information, thus allowing change detection and identification (Becker et al. 2000; Rensink et al. 1997).

Now, for simplicity, let us assume that the scene an imaginary observer is looking at consists of six elements, say A, B, C, D, E, and F, and that, because of top-down and bottom-up factors, A and B are ranked at the top of the priority list, whereas E and F are ranked at the bottom. What is supposed to happen if one of these items change? As discussed previously, if no other extraneous transient is present, the transient accompanying the change is registered by low-level mechanisms in the visual system, which responds by aligning attention to the transient location (Breitmeyer and Ganz 1976; Jonides 1981; Klein et al. 1992). As already suggested by O’Regan et al. (2000); also see O’Regan (2001), if a high-priority object changes, say that A changes into A′, before being summoned to the change location as a consequence of the visual transient, focused attention would have been deployed to A many times during scene exploration, thus allowing object characteristics to be stored in a relatively durable representation in working memory (WM). By comparing A′ with the stored representation of A, an observer should be able to identify how A′ differs from A. In other words, the observer should not only be able to detect the change, but also to identify it. If a low-priority item changes, say F changing into F′, the visual transient will always capture attention, thus ensuring an efficient change detection. However, because F was only marginally (or not at all) visited by attention before change, its related information was not stored and consolidated, and therefore no comparison with the current visual representation, now containing F′, would be possible. It follows that for objects of marginal interest change detection should always be possible, whereas change identification should be very difficult (also see O’Regan et al. 2000; O’Regan 2001).

We believe that there are at least two reasons that justify a direct test of change perception mechanisms when the only transiet visible is that caused by the change itself. At a general level, it should be noted that, although very plausible, the aforementioned hypothesis on change perception mechanism stems from what is known about mechanisms governing attentional orienting (Yantis 2000) and visual WM (Irwin 1991; Luck and Vogel 1997) but has not been tested directly in a situation where the observer is explicitly looking for a change. Indeed, O'Regan and his collaborators already pointed out that "... this prediction about seeing changes under normal conditions has not been studied empirically. It may correspond to the 'what was that?' situation which one encounters sometimes when one has the impression that something has happened in the visual field, without knowing exactly what it was. Certainly further work would be useful to determine to what extent people miss marginal interest changes that take place in full view under normal conditions" (O'Regan et al. 2000, p. 207).

In addition, it would be useful to explore how visual attention and WM interact to ensure efficient change perception (Rensink 2002). In particular, this interplay could be of interest for change perception in a multi-element display containing objects of central and marginal interest. The existence of strong links between attention and WM has been suggested by many previous models of visual attention, which posit that these two cognitive functions cooperate particularly during visual search (e.g., Cave 1999; Wolfe 1994). For example, WM would be relevant to maintain a search template of the target, and to perform a matching between such template and the item attended at any given time (Bundesen 1990; Duncan and Humphreys 1989). In addition, Desimone and Duncan (1995; Desimone 1998) have also proposed that the content of WM can influence the deployment of visual attention by biasing the representation of the stimulus held in memory. Besides being confirmed by cell recording studies (e.g., Chelazzi et al. 1998), this prediction has recently gained important support from a behavioral study by Downing (2000), who showed that attention shifted to the location of the stimulus held in WM, even if information in WM was irrelevant for the spatial attention task.

However, in all these studies the effect of WM on spatial attention allocation has been evaluated when a single stimulus, either the target of the visual search or the item to be remembered for further comparison, was held in memory. In contrast, for the present study (Experiments 1 and 2) we required participants both to detect and identify a change in one of many objects presented in the display. Because we used three different colors to assign three different priorities of change to 12 different objects (thus creating objects of central and marginal interest), participants had to keep in memory more than one element (possibly four; Luck and Vogel 1997). In principle, participants should try to memorize the shapes of those objects sharing the color having the greatest probability of a change. So, one might wonder whether, in a change perception task, the allocation of visual attention could be biased to those items matching the search template in WM. Since in the present study the search template was defined on the basis of color, this would entail that participants could be able to pay attention to different objects of the same color in the multi-element display. This would be far from trivial, as previous studies did not find evidence that attention can be selectively allocated to objects of a given color during visual search, when they are scattered among other objects (of different colors) in the scene (Treisman 1982; Tsal and Lavie 1988). Can WM affect attention allocation in a change perception task, thus leading to evidence for color selectivity? To anticipate, contrary to previous studies, we found that, under the present experimental conditions, evidence for color selectivity emerged when a luminance change detection was coupled with a WM task. The specific role of WM was confirmed in Experiment 3, as when the memory task was removed, selectivity for color disappeared.

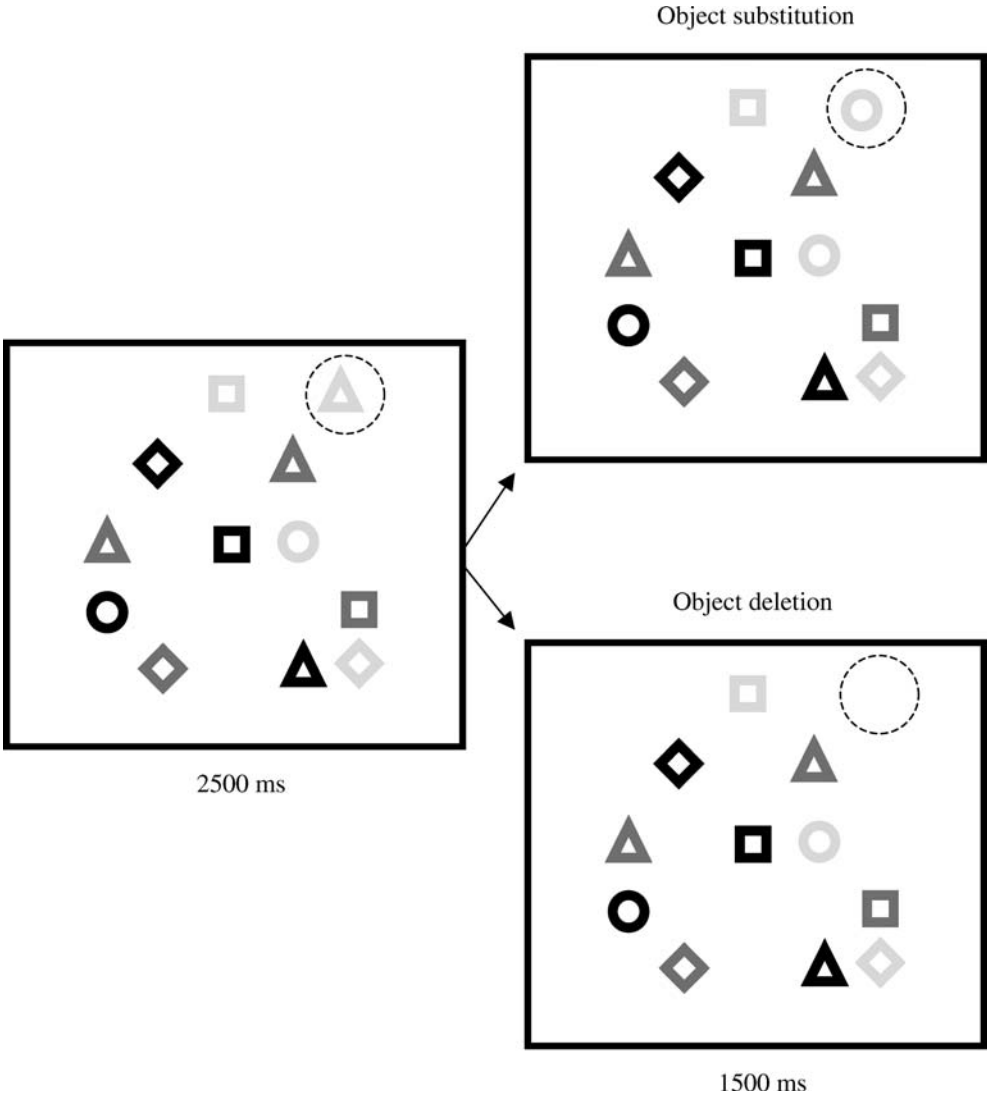
Among the various types of changes, we chose to investigate the changes caused by object substitution and by object deletion, which might be considered two of the largest modifications that might potentially occur in a scene. For each type of change we explored change detection [by considering detection response times (RTs) and proportion of missed changes], and change identification (proportion of errors).

Experiment 1

Previous studies on change blindness have provided evidence that if the visual transient accompanying a change is masked or attenuated, an object can be modified or substituted without observers noticing any change in the scene (Rensink et al. 1997). In contrast, if visual continuity is not disrupted by other extraneous transients, the change should be easily perceived because the only visual transient is that associated with the change (e.g., Rensink et al. 1997; Turatto et al. 2003). In the present experiment we explored change perception when the scene modification consisted of a given shape changing into a different one (e.g., a triangle changing into a circle, see Fig. 1, upper panel). In this and the following experiments we used objects of familiar shapes, as previous studies showed that object familiarity seems not to be an issue in change perception (Pashler 1988).

As we noted, perceiving a change is a visual function that can be distinguished in two separate processes, change detection and change identification. Therefore, we asked participants to perform two tasks upon scene modification. When a change occurred they had to detect it first as quickly as possible. Then, without time pressure, they were also asked to identify the shape that had been changed. There is reason to believe that change detection can mainly rely on 'peripheral' visual mecha-

Fig. 1 Example of the stimuli and events used for Experiments 1 (*upper panel*) and 2 (*lower panel*). The different objects' colors are represented as differences in *gray level*, whereas the background was *black*. In this example, object substitution consists of a *triangle* changing into a *circle*, whereas in the case of object deletion the triangle disappears. The *dashed circle* (not present in the real display) indicates the location of change



nisms processing luminance changes in parallel across the visual field (Braw and Snowden 1999; Snowden and Hess 1992). In contrast, change identification would rely on 'central' high-level mechanisms, such as a capacity-limited WM (Irwin 1991; Luck and Vogel 1997; Rensink et al. 1997), in which attention selectively transfers information from early fast-decaying visual buffers (Coltheart 1980; Di Lollo and Dixon 1998; Rensink 2002).

To study change perception when the corresponding transient is present, we presented two images, separated by a zero interstimulus interval (ISI), identical in all aspects except for one object that, on some trials, might change into a different one. The exposure time of the first image was set at 2,500 ms, whereas that of the second image was set at 1,500 ms. By using such a long exposure time for the first display we gave observers enough time to engage in multiple attentional scanning of the image without any extraneous transients (for examples of other change blindness studies using long exposure durations see Beck and Levin 2003; Simons 1996). This would allow them to store information selected by attention in WM, and to use such information for later comparisons when a change occurs.

Method

Participants

Twelve psychology students from the University of Trento served as participants. Their average age was 22.6 years, and all were unaware of the purpose of the experiment.

Apparatus and stimuli

All experiments were conducted in a room with normal illumination (approximately 50 cd/m^2). Participants sat in front of a computer monitor at a viewing distance of 50 cm. The display consisted of 12 geometrical shapes (randomly chosen on each trial between squares, circles, triangles, and diamonds) occupying random positions in a 5×5 matrix (Fig. 1), and presented over a black background (about 2 cd/m^2). Each shape had the same spatial extent, covering approximately 1° of visual area. One-third of the stimuli were colored in red, one-third in blue, and the remaining in green. Colors were matched for luminance by means of a Minolta chromameter CS-100, and were set, on average, at a luminance of 12.8 cd/m^2.

Stimuli were presented on a LCD monitor (active matrix technology), driven by a 640×480 graphic board. The choice of this type of monitor was motivated by the fact that any possible role of screen persistence in change perception due to phosphors fading is eliminated. In addition, the experiment was performed under normal room illumination, to reduce any effects of afterimages (see discussion of Experiment 2).

Design

The only factor involved was object priority, with three levels (high, medium, and low). Object priority was manipulated by assigning different probabilities of change to objects of each color. The probability of change was 60, 30, and 10% for high-priority, medium-priority, and low-priority objects, respectively. Because participants were clearly informed about this contingency, this manipulation had the intention to define a 'list of priority' affecting attentional allocation to objects in the display. In other words, this should create objects of 'central' and 'marginal' interest as in previous change blindness studies (Rensink et al. 1997). The color assignment to the three probabilities of change was counterbalanced across participants.

Participants were given three experimental blocks of 60 trials each. In each block the change, when present, occurred as follows: 30 trials in the high-priority color, 15 in the medium-priority color, and five in the low-priority color. This left 10 trials in which no change was presented, which served as catch trials. A block of 14 training trials was performed by the participants at the beginning of the experiment. Data from this block of trials were not analyzed.

Procedure

Before the experiment began, instructions emphasized the contingency between objects of a given color and its related change probability. Each trial began with the presentation of 12 objects for 2,500 ms. Then, on change present trials, an object changed into another (e.g., a circle became a triangle). The color of the changed object remained the same. After the initial 2,500 ms was elapsed, and regardless of whether a change occurred, participants were given 1,500 ms for responding to the presence of a change (if any). During this time, the display remained visible on the screen. Participants were instructed to react as quickly as possible to any change in the display by pressing the spacebar on the computer keyboard, but to refrain from responding if nothing changed. If they correctly detected a change, then a message on the computer screen required them to identify the shape that was substituted. Participants provided their response by pressing, without time pressure, the corresponding shape initial letter on the keyboard (e.g., 'c' for circle; 't' for triangle). Feedback messages were sequentially provided both for change detection (missed changes and false alarms) and, when the change was present, for change identification (feedback was given only in case of a wrong identification response).

Results

In this and in the following experiments, before analyses on RTs were carried out, RTs above 2 SD from the mean and below 150 ms were deleted as outliers. As a consequence of the outlier-latency criterion, 1.5% of the data were trimmed in the present experiment.

Change detection

Response times from the change detection task were entered into a repeated measures analysis of variance (ANOVA), in which the factor object priority was significant, $F(2,22) = 4.464$, $P < 0.024$. The results indicated that RTs for change detection varied as a function of object priority (see Fig. 4). Participants were slower at detecting a change in the low-priority objects ($M = 501$ ms, SD = 84) and the medium-priority objects ($M = 500$ ms, SD = 70), and faster in the high-priority objects ($M = 484$ ms, SD = 76). Planned comparisons (*t*-tests, two-tailed) revealed that RTs were significantly shorter when the change occurred in high-priority objects than in either medium-priority objects $t(11) = 2.888$, $P < 0.015$, or low-priority objects $t(11) = 2.381$, $P < 0.036$. In contrast, RTs did not differ between low- and medium-priority objects ($P = 0.813$).

Percentages of correct change detection (Fig. 2) were entered into a repeated measure ANOVA. The factor object priority was significant, $F(2,22) = 5.597$, $P < 0.009$. Planned comparisons revealed that change detection accuracy was slightly although significantly affected by object priority: low-priority objects ($M = 88\%$, SD = 9), medium-priority objects ($M = 92\%$, SD = 5), high-priority objects ($M = 94\%$, SD = 4). Planned comparisons confirmed that participants were more accurate in detecting a change in high-priority objects than in low-priority objects $t(11) = 3.160$, $P < 0.009$. In addition, change detection was, in general (trend toward significance), more accurate for high-priority objects than medium-priority objects $t(11) = 1.753$, $P < 0.107$, and more accurate in medium-priority objects than in low-priority objects $t(11) = 1.879$, $P < 0.087$.

The number of false alarms (i.e., responses on catch trials) was very low (less than 2% in this and the following experiments), and was not further analyzed.

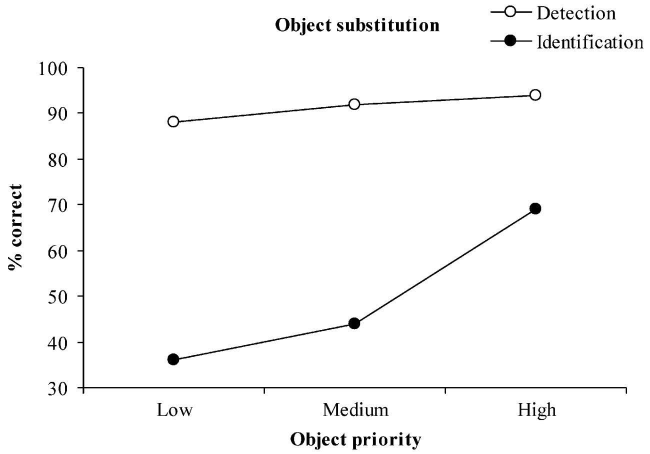


Fig. 2 Percentage of correct target detection and identification during object substitution as a function of object priority in Experiment 1. Chance level for change identification was 33%

Change identification

The participants' ability to identify a change as a function of object priority was evaluated by entering percentages of correct change identification into a repeated measure ANOVA (the percentages refer to trials where the change was correctly detected. This also holds for Experiment 2). The factor object priority was significant, $F(2,22) = 14.095$, $P < 0.0001$. As confirmed by planned comparisons change identification was clearly mediated by the way attention was allocated to the display that is according to object priority (see Fig. 2). Accuracy in change identification was higher in the high-priority objects ($M = 69\%$, SD = 17) than in either the medium-priority objects ($M = 44\%$, SD = 6), $t(11) = 3.957$, $P < 0.002$, or low-priority objects ($M = 36\%$, SD = 15), $t(11) = 4.315$, $P < 0.001$. In addition, change identification in the low-priority objects was not significantly different neither from medium-priority objects ($P = 0.170$), nor from chance level (36% vs. 33%, $P = 0.442$). However, change identification in the medium-priority objects differed from chance level (44% vs. 33%), $t(11) = 5.700$, $P < 0.0001$.

Discussion

In this experiment a change in an object could be detected whether attention was directed to it or not, while change identification was successful only for those objects that were particularly attended (i.e., objects of high priority). These results are consistent with the hypothesized mechanism for change perception when extraneous visual discontinuities are removed (O'Regan et al. 2000; O'Regan 2001). To study the different impacts of attention and memory on change perception we needed to differentiate the allocation of the two cognitive functions to objects in a multi-element display. However, instead of relying on participants' spontaneous reports to define objects of central and marginal interest (e.g., Rensink et al. 1997), we created such priority by varying the contingency between objects' color and probability of change. When informed of such a contingency, participants were motivated to mainly attend to those objects that had the largest likelihood to be changed.

Results depicted in Fig. 2 indicate that when extraneous transients are absent, perceiving a change consisting of an object substitution, is a process that can be divided into two distinct functions: change detection and change identification. Change detection was only marginally, although significantly, affected by attention allocation prior to change. In this case, the maximum difference in performance between objects of central (i.e., high priority) and marginal interest (medium and low priority) is 6%. The modest decrement from a 100% performance, one would expect, can be accommodated by assuming that occasionally the change occurred during blinks or eye movements (Grimes 1996; Deubel et al. 2004). In contrast, change identification heavily depended on which information visual attention has selected and transferred from the display into WM. The low-priority objects condition shows a percentage of correct change identification that is not different from chance level, whereas in the high-priority change condition participants correctly identified the change 69% of the time. This difference is ten times greater than in the change detection task.

Also of interest is the RT pattern that emerged from the change detection task. From the predictions about change perception in the absence of extraneous transients, there were reasons to expect RTs for change detection to be unaffected by object priority. When an object in the scene is replaced by a different one, the corresponding visual transient is detected by transient detector mechanisms in the observer's low-level visual system. This, in turn, elicits a neural response in the cortical and subcortical neural structures controlling visual orienting behavior, which exogenously directs attention to the location of the transient (Breitmeyer and Ganz 1976; Corbetta and Shulman 2002). In addition, hard-wired mechanisms for luminance change detection seem to operate in parallel over the entire visual field (Snowden and Hess 1992). Accordingly, Brawn and Snowden (1999) asked their participants to detect a luminance increment (the target) as quickly as possible in one of either the red or green items in a multi-element display. Before each block of trials, participants were informed about the color of the objects among which the luminance change took place. Though this information should have favored the allocation of attention toward the relevant color, RTs for change detection were unaffected by knowledge of target color. In contrast, in the present experiment we found a clear modulation of attention allocation towards a specific color (that defined objects of central and marginal interest) during a change detection task, in which the change was caused by a modification of the luminance pattern at retinal level. RTs for change detection were shorter for objects of central interest and longer for objects of marginal interest. In the GD we will provide an explanation for the discrepancy between this result and that of Brawn and Snowden (1999).

Overall, the results of Experiment 1 unambiguously show that the possibility of identifying a change correctly is strongly affected by allocation of visual attention in the display prior to change occurrence. During scene exploration before change, objects of central interest receive more attentional resources than other objects, which results in a higher probability that their related information is transferred into WM. In the case of object substitution, the possibility of storing information in WM is crucial to change identification, since information in early sensory storage systems is subjected to overwriting by new input at the same spatial coordinates (Becker et al. 2000; Rensink et al. 1997). In accordance with this view, in the present experiment the appearance of the new object caused information from the object previously occupying the same position to be lost, due to overwriting at a sensory storage level. However, if by means of attention the old-object identity is consolidated in WM, which is not subjected to erasure by new visual information (Gegenfurtner and Sperling 1993), then a comparison is possible with the current visual representation, thus allowing the change to be identified correctly. By contrast, if the old object is marginally visited by attention, as in the case of low-priority objects and to a lesser extent of medium-priority objects, related information will be lost when the new object replaces the previous one, thus making change identification difficult.

Experiment 2

On the basis of Experiment 1 we concluded that unless attention moved object information from fast-decaying visual buffers to a more durable storage such as WM, the appearance of a new object overwrote information about the previous object at the same location. This rendered comparison between the contents of the current visual representation with those of the previous one impossible, and change identification failed (also see Rensinsk et al. 1997). In contrast, comparisons should be possible between the ongoing visual representation and the contents of WM, as WM is not maskable by new information. As an example, in Experiment 1, this sort of comparison allowed change identification by confronting what was visible at a change location after the change (the new object), with what was stored in visual WM (for the same spatial coordinates), which corresponds to what was there before change.

However, if a change consists of object deletion, change identification might take advantage of comparison between the current visual representation and the contents of three potentially different kinds of fast-decaying visual buffers. Two of them, visible persistence and retinal afterimages, are visible, whereas iconic memory, although referring to a visual property, is not visible (Coltheart 1980). For the moment, the three kinds of persistence will be referred to as visual persistence, which indicates only that it has something to do with early mechanisms of information storage in the visual system, which are sensitive to masking. One logical implication is that if information from visual persistence can be used after stimulus offset, stimulus identification should eventually be possible regardless of whether attention has previously consolidated object information in WM. In other words, in the case of object deletion, as compared to object substitution, change identification should depend much less on where attention is deployed before the change takes place. Put differently we might predict that change identification should depend only slightly on object priority.

Method

Participants

Twelve psychology students from the University of Trento served as participants. Their average age was 23.7 years, and all were unaware of the purpose of the experiment.

Apparatus and stimuli

The same as in Experiment 1.

Design and procedure

As in Experiment 1 except that the change consisted of a shape that disappeared from the display (Fig. 1, lower panel).

Results

As a consequence of the RT outlier-latency criterion, 1.8% of the data were trimmed in this experiment.

Change detection

Response times from the change detection task were entered into a repeated measures ANOVA, in which the factor object priority was significant, $F(2,22)=3.865$, $P<0.036$. Planned comparisons showed that participants were faster at detecting a change in the high-priority objects ($M=515$ ms, SD = 98) compared to the medium-priority objects ($M=537$ ms, SD = 102), $t(11)=3.282$, $P<0.007$, whereas the difference between high-priority objects and the low-priority objects ($M=532$ ms, SD = 106) was only marginally significant, $t(11)=1.807$, $P<0.098$. Overall, the results were consistent with RT data of Experiment 1, suggesting a selective allocation of attention to objects of central interest (see Fig. 4).

We next analyzed change detection considering accuracy as the dependent variable. Percentages of correct change detection (Fig. 3) were entered into a repeated measure ANOVA. The factor object priority did not approach significance ($P = 0.203$), revealing that change detection accuracy did not vary as a function of objects of central and marginal interest.

Change identification

The impact of object priority on change identification was evaluated in a further ANOVA, in which the factor object priority was significant, $F(2,22) = 7.042$, $P < 0.004$. Planned comparisons showed that change identification varied as a function of object priority (see Fig. 3). The percentage of correct change identification was higher in the high-priority objects ($M = 90\%$, $SD = 8$) than in either the medium-priority objects ($M = 75\%$, $SD = 15$), $t(11) = 3.238$, $P < 0.008$, or the low-priority objects ($M = 79\%$, $SD = 17$), $t(11) = 2.408$, $P < 0.035$. The difference between medium-priority objects and low-priority objects was not significant ($P = 0.201$), but for both conditions the percentage of correct change identification was higher than chance level (for both $P < 0.0001$).

Discussion

The first consideration, which the present results deserve for the kind of display and stimuli used here is that visual persistence plays a clear role in object identification after an object has disappeared. This is immediately evident when one compares accuracy of correct change identification, for each level of object priority, in Experiment 2 with that of Experiment 1, in which we can expect backward masking from the new object to suppress persistence from the previous object, preventing identification of the old object from persistence alone. These differences (for all, $P < 0.001$) suggest that when some sort of visual persistence can be used after stimulus offset to retrieve object identity information, change identification is improved. This is particularly evident when low and medium levels of object priority are considered. For example, when the low-priority objects are considered, object substitution identification accuracy was 36% (which did not differ from chance level, 33%), whereas for object deletion it rose to 79%. Put differently, in the present change identification task some sort of visual persistence can be used to escape the limits imposed by attention in transferring information in a more durable storage such as WM.

However, note that using information from visual persistence also has a positive effect on high-priority objects, where performance was better for object deletion ($M = 90\%$) than for object substitution ($M = 69\%$). This might indicate that the process of moving information from sensory storage to WM is not perfect, or alternatively that four attended objects represent the limits of attention or WM (Irwin 1991; Luck and Vogel 1997). However, one could speculate that the lower percentage of change identification in the case of object substitution as compared to object deletion, might be attributed to the fact that the process of retrieving information from WM about the object that has been changed could suffer some degree of interference from the new object's identity at the same location. This, however, does not apply to the case of deletion, as no new object replaces the one that disappeared. Finally, one should also consider that, unlike in natural scenes, interference in retrieving the identity of the changed object may arise also because we used an array of similar and easily confusable objects.

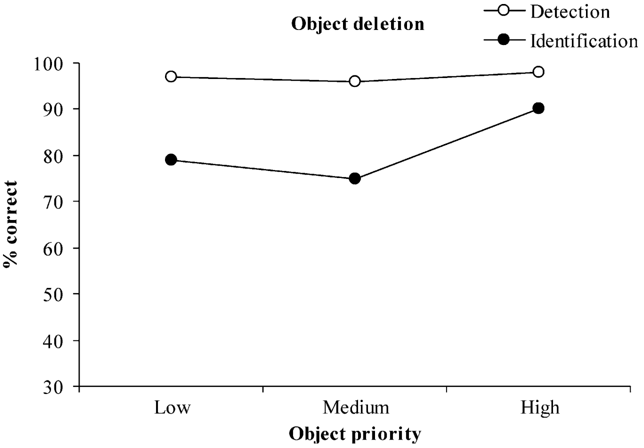
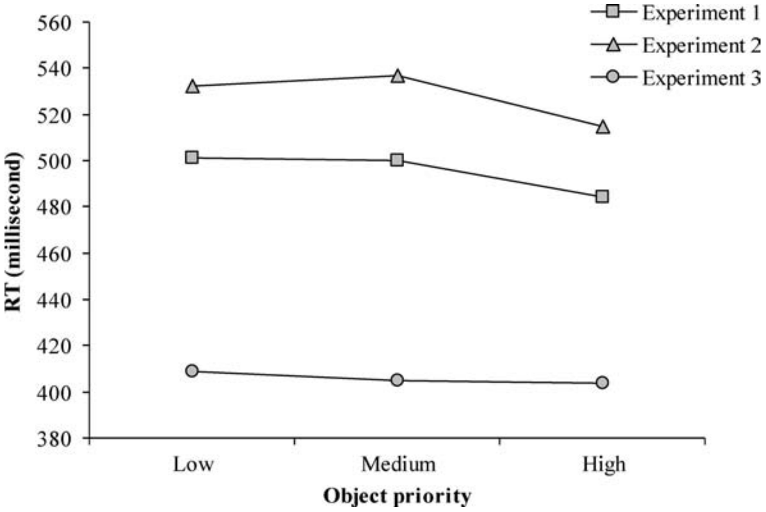


Fig. 3 Percentage of correct target detection and identification during object substitution as a function of object priority in Experiment 2. Chance level for change identification was 33%

At this point we might ask whether the results are of any help in distinguishing the type of visual persistence involved in the present experiment. What kind of visual persistence might have improved change identification as compared to Experiment 1? Room, background, and stimulus luminance produced a retinal illumination of approximately 30 Td, a value that is not in the range typically thought to elicit retinal afterimages (Coltheart 1980). Moreover, had retinal afterimages been the cause of improvement in performance, participants should have seen the afterimage of the disappearing object moving on the screen as they turned their eyes toward the location of change. Importantly, none of the participants (nor one of the authors, M. Turatto, during informal observation) reported having seen any afterimage shifting in the direction of eye movement. Visible persistence can be ruled out as well, given that, before disappearing, the target stimulus remained visible for at least 2,500 ms. In fact, visible persistence has a maximum duration of about 300–500 ms from stimulus onset (Coltheart 1980; Di Lollo and Dixon 1988).

As far as iconic memory is concerned, Becker et al. (2000) investigated the role of this type of short-lasting

Fig. 4 Mean RT as a function of object priority in Experiments 1, 2, and 3



visual buffer when participants looked for a change between a pair of images separated, at variable ISI, by a blank. The authors provided convincing evidence that during the blank, information from the first display is stored in an iconic memory form. Unless stored in WM via attention, this information is either subjected to fast decay or to overwriting by new information once the second display is presented. This mechanism would explain why items that are not attended are not seen changing in the flicker paradigm, thus producing the change blindness phenomenon (also see Rensink et al. 1997). Since in the present experiment the changing object was deleted without being replaced, it seems plausible to hypothesize that observers used the spatially localized visual transient to recover information stored in iconic memory to identify the object after its offset.

Although it is clear that object deletion particularly improved change identification as compared to object substitution, we also found that change detection was slightly, although significantly, better for object deletion than for object substitution ($P < 0.05$ for all levels of priority). Different reasons could explain this difference. First, one should note that with the type of visual scene used here when an object disappears it is the configuration of the whole scene which is destabilized. Given that changes in layout are easier to detect than single local changes (Simons 1996; Simons and Wang 1998), this might explain why change detection was higher for object deletion as compared to object substitution, as in the latter case the layout was not modified by the change. Although we recognize that this may be, in general, a viable explanation, we would also like to note that there are reasons to suspect that changes in layout due to deletion were difficult to detect in the present study, as the gist of the scene remained the same, namely a random array of simple objects. In other words, the meaning of the scene did not change as one object disappeared. A second possibility to explain change detection improvement for object deletion calls into question the fact that the visual transient caused by a deletion was greater than that caused by a substitution, thus increasing the probability that the change was noticed. Hence, deletion, as compared to substitution, improved identification as well as detection, even though the improvement was larger in the former than in the latter. However, one should also note that change detection performance could not improve too much from substitution to deletion, as it was already almost at ceiling in the case of object substitution.

Overall, however, results from the present experiment were in line with two important results that emerged from Experiment 1. First, although in the case of object deletion change identification was very good even for objects of marginal interest, it still remained more difficult than change detection (see Fig. 3). Second, RTs for change detection confirmed that attention can be selectively allocated to objects of a particular color (cf. Brawn and Snowden 1999). The next experiment explored this unexpected pattern of results in more detail.

Experiment 3

In both Experiments 1 and 2 participants were faster at detecting the change in objects of central interest (high-priority objects) than in objects of marginal interest (medium- and low-priority objects). Since we defined object priority on the basis of color, this seems to indicate that participants were able to selectively attend to the objects of the relevant color in the display. This, however, is at odds with previous findings showing that attention cannot be distributed to different scattered items of the same color in a display (Brawn and Snowden 1999; Treisman 1982; Tsal and Lavie 1988). Indeed, with regard to this point Treisman (1982, p. 199) already noted that " ... attention cannot be distributed over a subset of items (e.g., the red ones) when these are spatially scattered among other items in a random mixed display". Brawn and Snowden (1999) confirmed this prediction, showing that participants were not faster at detecting a luminance change in one of many items of two possible colors when the color of the changing item was known as compared to when it was unknown. By contrast, attention to color selectivity emerged when the task switched from a simple luminance change detection to luminance change discrimination. The authors explained their findings relating attention effect to the type of task (detection vs. discrimination) by suggesting that attentional effects are evident only in the case of a discrimination task (Brawn and Snowden 1999; also see Bravo and Nakayama 1992).

In fact, results from Experiments 1 and 2 seem to support the idea that attention can be modulated by color using a simple change detection task. Note that the type of task we used in both object substitution and deletion conditions involved a luminance change detection task, so in this sense our task was similar to that of Brawn and Snowden (1999). Instead, an important aspect that differentiates our study from previous ones is that in Experiments 1 and 2 change detection was combined with an unspeeded WM task. Hence, possibilities exist that information encoded and stored in WM might modulate, to some extent, the allocation of visual attention in the change detection task.

If our hypothesis is correct, we predict that RTs for change detection should not vary as a function of object priority, that is, as a function of color, when participants had only to perform the change detection task, without change identification.

Method

Participants

Twelve psychology students from the University of Trento served as participants. Their average age was 25.2 and all were unaware of the purpose of the experiment.

Apparatus and stimuli

As in Experiment 1.

Design and procedure

As in Experiment 1, except that the task required only detecting the change as quickly as possible, with no questions about change identification.

Results

As a consequence of the RT outlier-latency criterion, 1.7% of the data were trimmed in this experiment.

Response times from the change detection task were entered into a repeated measures ANOVA with object priority as a factor. Contrary to the results of Experiment 1, object priority was not significant, $F(2,22) = 0.723$, $P = 0.496$. RTs for change detection did not vary as a function of object priority (see Fig. 4): high-priority objects ($M = 404$ ms, SD = 76), medium-priority objects ($M = 405$ ms, SD = 73), low-priority objects ($M = 409$ ms, SD = 70). Note that RTs for change detection were, on average, 100 ms faster in this experiment than in Experiment 1 ($P < 0.\ 001$). This is a well known effect attributable to the fact that there is a cost in performance when two responses need to be scheduled, even if for the second response there is no time constraint (Umiltà et al. 1992).

Change detection was also analyzed considering accuracy as the dependent variable. Percentages of correct change detection were entered into a repeated measures ANOVA, in which the factor object priority was not significant ($P = 0.079$). The trend towards significance was caused by a modest decrement of the percentage of change detection in the low-priority objects condition ($M = 92\%$) as compared to both medium- and high-priority objects conditions (both $M = 96\%$).

Discussion

Results from Experiment 1 (also see Experiment 2) showed that attention was selectively allocated to objects of central interest when these were defined on the basis of color. Such attention color selectivity was possible even when objects of central interest were spatially scattered among other objects of marginal interest defined by different colors. This conclusion was supported not only by change identification accuracy, but, crucially, also when the RTs for change detection were considered. Indeed, RTs were significantly shorter for the high-priority objects (central interest) as compared to the medium- and low-priority objects (marginal interest).

Interestingly, however, the present experiment showed that the same change detection task failed to show evidence that attention can be modulated by color when the involvement of WM was largely reduced by excluding the unspeeded change identification task after change detection. Indeed, under this condition RTs did not vary as a function of object priority. This was confirmed by the fact that the RT advantage of the central-objects condition (high-priority objects) over the marginal-objects condition (medium- and low-priority objects) was larger in Experiment 1 (16 ms) than in Experiment 3 (3 ms) ($P < 0.04$).

The results from Experiment 3 are consistent with those of previous studies showing that luminance change detection was not altered by attention (Bonnel et al. 1992; Brawn and Snowden 1999; Snowden and Hess 1992). Yet, results from the change detection task in Experiments 1 and 3 taken together seem to suggest that attentional modulation by color can be found if the attended objects have to be stored in WM.

General discussion

In the last decade many studies have been dedicated to the change blindness phenomenon (Simons and Levin 1997; Rensink 2002). The interest raised by change blindness is, at a more general level, due to the fact that it provides a striking example of how important attention is to visual perception, and how 'blind' we may be under some, not infrequent, conditions (e.g., during a blink of the eye, O'Regan et al. 2000). More specifically, however, change blindness has proven to be a productive research topic in vision, as studying change blindness can reveal how various cognitive functions, such as attention and memory, interact to build up our conscious visual experience. In a change blindness study the importance of focused attention (and memory) for change perception is demonstrated by removing or reducing the salience of the visual transient that normally accompanies a change. This can be done by changing in the blank period between a pair of images (Rensink et al. 1997) or during blinks or saccades (Bridgeman et al. 1975), by presenting other irrelevant objects at the time of change (O'Regan et al. 1999), or by reversing the image polarity (Turatto et al. 2003). Since attention can process only a limited number of elements at any given time, finding a change in a complex scene that is repeatedly occurring under our eyes can require a surprisingly long time.

The basic assumption behind all change blindness studies is that when the only transient present in the scene is that accompanying the change, then change detection should always be possible, whether it takes place in objects of central or marginal interest. In contrast, change identification should be feasible for the former but severely impeded for the latter. On the basis of what is known about attention and memory mechanisms there might be a general agreement on these predictions about seeing changes when extraneous transients are removed, although these have remained only as speculations (O'Reagn et al. 2000; O'Regan 2001).

Hence, the main aim of the present study was to verify empirically mechanisms of change perception for object substitution and deletion when no extraneous disturbances are imposed at the time of change. We intentionally used the term 'change perception' to note that this process may involve at least two distinct mechanisms, change detection and change identification.

Results from Experiment 1 showed that change identification was accurate for objects of central interest (high-priority objects), but was very inaccurate for objects of marginal interest (medium- and low-priority objects), with change identification not different from a chance level when the change took place in objects of marginal interest. This presumably occurred because the representation of unattended objects is only temporarily stored in a visual buffer such as Iconic memory, which is subjected to masking from incoming information at the same location (also see Beck and Levin 2003; Becker et al. 2000; Rensink et al. 1997). In contrast, identity of attended objects is transferred into WM, which is not vulnerable to masking (Gegenfurtner and Sperling 1993), and can be used for comparison with post-change objects. As is evident from Fig. 2 , accuracy on change detection was higher than for change identification, although it slightly declined from 100% as a function of object priority. This optimal performance would be attributable to the fact that luminance change detection is ensured by low-level mechanisms that pick up visual transients in parallel across the retina (e.g., Snowden and Hess 1992). Results from Experiment 2 confirmed different performances between detection and identification, also showing that, for each level of object priority, change identification accuracy was higher than in Experiment 1. Change identification was easier when an object disappeared than when it was substituted (i.e., masked) by a new one. In a visual display like that used here, in which the objects were presented over a black background, when an object disappeared the observers still had the possibility to retrieve object's information from Iconic memory. This would allow a comparison between the post-change and pre-change objects that were not entered in WM, which would result in object identification improvement even for objects of marginal interest.

Overall, a clear difference emerges between change detection and change identification, as the former is almost perfect and virtually independent of attention allocation (but see discussion on RTs), whereas the latter is affected by where attention is located at the time of change. This empirically confirmed the hypothesized mechanisms of change perception (also see O'Regan et al. 2000; O'Regan 2001), indicating that change detection and identification rely on different mechanisms, and as such, the two terms should not be used interchangeably. A distinction between detection and recognition (or identification) has also been suggested by Beck and Levin (2003; also see Watanabe 2003) when the change is made to occur across the blank between two images. However, when extraneous transients are absent at the time of change, change detection refers only to noticing that something has changed because of the registration of a visual transient in the scene. In contrast, change detection as intended by Beck and Levin (2003) refers to a more central process that operates when the visual transient is eliminated (e.g., by a blank between the pair of images), and that relies on comparisons between pre-change and post-change representations. Interestingly, it seems that there might be cases in which representations that are sufficient for change detection might not be sufficient for change recognition or identification (Beck and Levin 2003).

The fact that change detection accuracy was almost perfect both in Experiments 1 and 2 regardless of whether the change occurred in objects of central or marginal interest (although a modest decrement as a function of object priority emerged in the detection task of Experiment 1), suggests that luminance change detection is performed in parallel over the entire visual field and is not altered by attention (Bonnel et al. 1992; Snowden and Hess 1992). Although previous studies indicated that attention cannot be selectively allocated to items of a given color when they are presented among other items of different colors (Treisman 1982; Tsal and Lavie 1988), we found that RTs for change detection were shorter for objects of central interest than for objects of marginal interest. This was also surprising given previous failures to show evidence for color selectivity in attention allocation when a change detection task was used (e.g., Brawn and Snowden 1999). Faster RTs for objects of central interest were also found in Experiment 2, in which the luminance change was determined by the disappearance of an item from the display. How can this finding be reconciled with previous findings of no attention selectivity for color using a simple RT task? One important difference is that, in contrary to previous studies, in Experiments 1 and 2 the change detection task was followed by an unspeeded memory task. The involvement of WM for change identification may have led participants to pay ‘more’ attention to the relevant objects (also see Agostinelli et al. 1986; Mondy and Coltheart 2000), which speeded RTs for objects of central interest as compared to objects of marginal interest in the change detection task.

An alternative explanation would call into question the relationship between the contents of WM and attention. In Experiment 1, two types of information were held in WM: the search template, which corresponded to the color with the highest probability of change, and, as the search went on, the identity of those objects having that color. In contrast, in Experiment 3 only the search template was likely kept in WM, as no change identification was required. The idea that the search template held in WM can bias the perceptual mechanisms to favor allocation of attention to those items that have common features with the template is predicted by some attention models (Bundesen 1990; Desimone and Duncan 1995; Duncan and Humphreys 1989). In the biased-competition perspective objects compete for attention as integrated wholes, so that attention to one feature of an object (e.g., its color) should bias attention to other objects on this dimension as well. If this were the case, one would predict that “...working memory for a single feature, such as the color red, should bias attention to any object with the same feature” (Downing 2000, p. 473). However, since it is reasonable to assume that participants used the search template to attend to a specific color in Experiment 1 as well as in Experiment 3, results from Experiment 3 seem to challenge this prediction, as no attention selectivity for color was observed in RTs when the task required only a change detection. This also suggests that it was not the template “search for items of a given color” per se that affected the allocation of attention in Experiment 1. Instead, attention appears to have been selectively allocated to those objects that matched the search template only when the shape identity of these objects was held in WM for change identification. Consistent with this idea, evidence has emerged recently that visual short-term memory is to a considerable extent object-based (Vogel et al. 2001; Wheeler and Treisman 2002). However, note that the discrepancy between the present results and those of Brawn and Snowden (1999) might be more apparent than real. Indeed, it should be noted that in Brawn and Snowden’s study, participants viewed displays with a greater number of elements (some displays contained upto 32 items) as compared to the 12 used in the present study. Hence, in our study, participants’ selectivity for color could have emerged because of the limited number of elements that needed to be attended to.

A final consideration regards the possible role of fixations in the present experiments. Although we did not monitor eye movements during display viewing, it is very likely that participants preferentially attended and gazed at objects of central interest to encode the corresponding information (i.e., shape) in WM (Henderson et al. 1999). Hence, if objects of marginal interest were not fixated, their information was unlikely to be entered in WM, and change identification failed. Accordingly, Henderson and Hollingworth (1999) showed that fixation position and saccade direction are crucial in determining whether changes are perceived. The authors asked their participants to memorize details of objects in a picture for a subsequent memory test, while monitoring the scene for changes. The change consisted of either an object rotation or deletion, and was arranged to occur during an eye movement that was directed either toward or away from the location of change. Because the change took place during an eye movement, the corresponding visual transient was swamped by motion signals due to the image’s retinal displacement. Hence, change detection in Henderson and Hollingworth’s (1999) study would be similar to change identification in the present study. In accordance with the results for change identification in objects of marginal interest in Experiments 1 and 2, Henderson and Hollingworth (1999) found that when neither the pre- nor the post-change fixation was on the changing object, participants missed the change 90% of the time in the case of rotation, and 60% of the time in the case of deletion. So, fixation position might have played a role in producing the priority effect in change identification. Similarly, one might argue that fixation position would also explain the priority effect when RTs for change detection are considered. Yet, results from Experiment 3 are at odds this view, as they did not show a priority effect on RTs, even though it seems reasonable to assume that participants fixated objects of central interest more than objects of marginal interest.

However, the possibility exists that the pattern of eye movements and fixations might have been different as a function of whether participants had, or not, to encode object identity in WM for change identification. There are indeed reasons to suspect strong links between eye movements and WM, as recent works showed that visual search is affected by a concurrent WM task (Oh and Kim 2004; Woodman and Luck 2004). Certainly further work should explore the relationship between eye movements during scene exploration for change detection and identification, and WM.

Acknowledgements The authors wish to thank Anna Daccordo for her help in data collection, and three anonymous reviewers for their helpful comments on an earlier draft of this manuscript. This research was supported by grants from Ministero della Istruzione, Università e Ricerca scientifica (MIUR) and University of Trento to M. Turatto.

References

Agostinelli G, Sherman SJ, Fazio RH, Hearst ES (1986) Detecting and identifying change: addition versus deletion. J Exp Psychol Hum Percept Perform 12:445–454

Beck MR, Levin DT (2003) The role of representation volatility in recognizing pre- and postchange objects. Percept Psychophys 65:458–468

Becker MW, Pashler H, Anstis SM (2000) The role of iconic memory in change detection tasks. Perception 29:273–286

Bonnel AM, Stein JF, Bertucci P (1992) Does attention modulate the perception of luminance change?. Q J Exp Psychol 44A:601–626

Bravo MJ, Nakayama K (1992) The role of attention in different visual search tasks. Percept Psychophys 51:465–472

Brawn P, Snowden RJ (1999) Can one pay attention to a particular color? Percept Psychophys 61:860–873

Brawn P, Snowden RJ, Wolfe JM (1999) The minimal conditions for "change blindness": what is replace what was. In: Poster presented at the annual meeting of the Association of Research in Vision and Opthalmology Fort Lauderdale

Breitmeyer BG, Ganz L (1976) Implications of sustained and transients channels for theories of visual pattern masking, saccadic suppression, and information processing. Psychol Rev 83:1–36

Bridgeman B, Hendry D, Stark L (1975) Failure to detect displacement of the visual world during saccade eye movements. Vis Res 15:719–722

Bundesen C (1990) A theory of visual attention. Psychol Rev 97:523–547

Cave KR (1999) The FeatureGate model of visual selection. Psychol Res 62:182–194

Chelazzi L, Duncan J, Miller EK, Desimone R (1998) Responses of neurons in inferior temporal cortex during memory-guided visual search. J Neurophysiol 80:2918–2940

Coltheart M (1980) Iconic memory and visible persistence. Percept Psychophys 27:183–228

Corbetta M, Shulman GL (2002) Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci 3:201–215

Desimone R (1998) Visual attention mediated by biased competition in extrastriate visual cortex. Philos Trans R Soc Lond B 353:1245–1255

Desimone R, Duncan J (1995) Neural mechanisms of selective visual attention. Annu Rev Neurosci 18:193–222

Deubel H, Bridgeman B, Schneider WX (2004) Different effects of eye blinks and target blanking on saccadic suppression of displacement. Percept Psychophys 66:772–778

Di Lollo V, Dixon P (1988) Two forms of persistence in visual information processing. J Exp Psychol Hum Percept Perform 14:671–681

Downing PE (2000) Interactions between visual WM and selective attention. Psychol Sci 11:467–473

Duncan J, Humphreys GW (1989) Visual search and stimulus similarity. Psychol Rev 96:433–458

Gegenfurtner KR, Sperling G (1993) Information transfer in iconic memory experiments. J Exp Psychol Hum Percept Perform 19:845–866

Grimes J (1996) On the failure to detect changes in scene across saccades. In: Akins K (eds) Perception: vancouver studies in cognitive sciences. Oxford University Press, Oxford UK, pp 89–110

Henderson JM, Hollingworth A (1999) The role of fixation position in detecting scene changes across saccades. Psychol Sci 10:438–443

Henderson JM, Weeks PA, Hollingworth A (1999) Eye movements during scene viewing: Effect of semantic consistency. J Exp Psychol Hum Percept Perform 25:210–228

Irwin DE (1991) Information integration across saccadic eye movements. Cogn Psychol 23:420–456

Jonides J (1981) Voluntary versus automatic control over the mind's eye's movement. In: Long JB, Baddeley AD (eds) Attention and performance IX. Erlbaum, Hillsdale, pp 187–203

Klein RM, Kingstone A, Pontefract A (1992) Orienting of visual attention. In: Rayner K (eds) Eye movements and visual cognition: scene perception and reading. Springer, Berlin Heidelberg New York, pp 46–65

Levin DT, Simons DJ (1997) Failure to detect changes to attended objects in motion pictures. Psychon Bull Rev 4:501–506

Luck SJ, Vogel EK (1997) The capacity of visual working memory for features and conjunctions. Nature 390:279–281

McConkie GW, Currie CB (1996) Visual stability across saccades while viewing complex pictures. J Exp Psychol Hum Percept Perform 22:563–581

Mondy S, Coltheart V (2000) Detection and identification of change in naturalistic scene. Vis Cogn 7:281–296

Oh S-H, Kim M-S (2004) The role of spatial WM in visual search efficiency. Psychon Bull Rev 11:275281

O'Regan JK (2001) Thoughts on change blindness. In: Harris LR, Jenkin M (eds) Vision and attention. Springer, Berlin Heidelberg New York, pp 281–302

O'Regan JK, Rensink RA, Clark JJ (1999) Change-blindness as a result of "mud-splashes". Nature 398:34

O'Regan JK, Deubel H, Clark JJ, Rensink RA (2000) Picture changes during blinks: looking without seeing and seeing without looking. Vis Cogn 7:191–211

Pashler H (1988) Familiarity and visual change detection. Percept Psychophys 44:369–378

Rensink RA (2002) Change detection. Annu Rev Psychol 53:245–277

Rensink RA, O'Regan JK, Clark JJ (1997) To see or not see: the need for attention to perceive changes in scene. Psychol Sci 8:368–373

Simons DJ (1996) In sight, out of mind: when object representation fails. Psychol Sci 7:301–305

Simons DJ, Levin DT (1997) Change blindness. Trends Cogn Sci 1:261–267

Simons DJ, Wang RF (1998) Perceiving real-world viewpoint changes. Psychol Sci 9:315–320

Singer W, Phillips WA (1974) Function and interaction of on and off transients in vision. II. Neurophysiology. Exp Brain Res 19:507–521

Snowden RJ, Hess RF (1992) Temporal frequency filters in the human peripheral visual field. Vis Res 32:61–72

Theeuwes J (1991) Exogenous and endogenous control of attention: the effect of visual onset and offsets. Percept Psychophys 49:83–90

Treisman A (1982) Perceptual grouping and attention in visual search for features and objects. J Exp Psychol Hum Percept Perform 40:201–237

Tsal Y, Lavie N (1988) Attending to color and shape: the special role of location in selective visual processing. Percept Psychophys 44:15–21

Turatto M, Galfano G (2000) Color, form, and luminance capture attention in visual search. Vis Res 40:1639–1643

Turatto M, Galfano G (2001) Attentional capture by color without any relevant attentional set. Percept Psychophys 63:286–297

Turatto M, Bettella S, Umiltà, C, Bridgeman B (2003) The perceptual conditions necessary to induce change blindness. Vis Cogn 10:233–255

Vogel EK, Woodman GF, Luck SJ (2001) Storage of features, conjunctions and objects in visual working memory. J Exp Psychol Hum Percept Perform 27:92–114

Warner CB, Juola JF, Koshino H (1990) Voluntary allocation versus automatic capture of visual attention. Percept Psychophys 33:129–138

Watanabe K (2003) Differential effect of distractor timing on localizing versus identifying visual changes. Cognition 88:243–257

Wheeler ME, Treisman AM (2002) Binding in visual short term memory. J Exp Psychol Gen 131:48–64

Wolfe JM, (1994) Guided Search 2.0: a revised model of visual search. Psychon Bull Rev 1:202–238

Wolfe JM (1999) Inattentional amnesia. In: Coltheart V (eds) Fleeting memories: cognition of brief visual stimuli. MIT Press, Cambridge, pp 71–94

Woodman GF, Luck SJ (2004) Visual search is slowed when visuospatial WM is occupied. Psychon Bull Rev 11:269–274

Yantis S (2000) Goal-directed and stimulus-driven determinants of attentional control. In Monsell S, Driver J (eds) Attention and performance XVIII. MIT Press, Cambridge, pp 73–104