Large capacity storage of integrated objects before change blindness

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Abstract

Normal people have a strikingly low ability to detect changes in a visual scene. This has been taken as evidence that the brain represents only a few objects at a time, namely those currently in the focus of attention. In the present study, subjects were asked to detect changes in the orientation of rectangular figures in a textured display across a 1600 ms gray interval. In the first experiment, change detection improved when the location of a possible change was cued during the interval. The cue remained effective during the entire interval, but after the interval, it was ineffective, suggesting that an initially large representation was overwritten by the post-change display. To control for an effect of light intensity during the interval on the decay of the representation, we compared performance with a gray or a white interval screen in a second experiment. We found no difference between these conditions. In the third experiment, attention was occasionally misdirected during the interval by first cueing the wrong figure, before cueing the correct figure. This did not compromise performance compared to a single cue, indicating that when an item is attentionally selected, the representation of yet unchosen items remains available. In the fourth experiment, the cue was shown to be effective when changes in figure size and orientation were randomly mixed. At the time the cue appeared, subjects could not know whether size or orientation would change, therefore these results suggest that the representation contains features in their 'bound' state. Together, these findings indicate that change blindness involves overwriting of a large capacity representation by the post-change display.
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1. Introduction

Although daily visual experience is rich in detail, our memory of what we have just seen appears pretty bad at times. The last couple of years, some striking demonstrations of a phenomenon called 'change blindness' have produced a growing interest in this issue. What was shown is that normal human subjects do not notice large changes in the visual world when these changes occur across brief disruptions like eye movements, blink intervals, blinks etc. (Grimes, 1996; O'Regan, Rensink, & Clark, 1999; Pashler, 1988; Phillips, 1974; reviews: Rensink, 2000a; Simons & Levin, 1997). Under normal conditions, changes are detected due to the transient produced by the change, which captures attention. Change blindness occurs when the change-transient is swamped by other transients, so that the change-transient is no longer the sole attention grabbing event (O'Regan et al., 1999). In this condition, change detection critically depends on the internal representation of the pre-change scene and the comparison with the post-change scene. The explanation of this phenomenon touches one of the main questions in psychology and neuroscience, namely 'How is the external world represented in the brain?'

While the early visual system is activated by elements throughout the visual field, change blindness has been taken as evidence for the fact that we consciously perceive only a subset of this information (O'Regan & Noe, in press). This is largely determined by attention. For example, in natural scenes, changes are more likely to be

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detected when they involve aspects of the scene that the observer thinks are important and meaningful, than when they involve aspects of marginal interest (O'Regan et al., 1999). When an exogenous cue draws attention to the target item in advance, change blindness does not occur (Scholl, 2000). People can monitor between one and four items for change (Luck & Vogel, 1997; Pashler, 1988; Rensink, 2000a), which is similar to estimates of attentional capacity (Pylyshyn & Storm, 1988; Rensink, 2000a; Scholl, 2001) and working memory capacity (Cowan, 2001). Change blindness thus suggests that the representation of unattended visual information is not retained across views. When an image disappears, the pre-attentive representation of the image (iconic memory, Sperling, 1960) decays within a few hundred milliseconds. Only using focused attention, a few items can be transferred to working memory for later use.

Attention is thought to be required to bind features into objects (Treisman & Gelade, 1980), and to encode a coherent representation of those objects for retention across disruptions (Rensink, 2000a). A pre-attentive representation with features in the 'unbound' state may exist, but this representation is highly volatile and will easily be overwritten by new information (Rensink, 2000a). Iconic memory is a pre-attentive representation. In the typical iconic memory experiment, an array of letters is briefly shown, and one row of letters is cued within about 800 ms after stimulus offset. While subjects can only report a few letters without the cue (whole report), they can report many of the cued letters, even though they have disappeared at the time of the cue (partial report). The cue allows subjects to shift attention to the cued items and transfer them from the volatile iconic memory to the more durable working memory (Coltheart, 1980; Gegenfurtner & Sperling, 1993; Sperling, 1960). Iconic memory has a large capacity but decays rapidly (<800 ms) and is maskable. Therefore it is highly volatile.

In the present study, we examined more closely the transition from iconic to working memory during a simplified one-shot change blindness paradigm. The fate of these internal representations across shifts of attention and visual disruptions is still not quite clear. Several hypotheses have been developed regarding the role of internal representations in change blindness (for review, see Simons, 2000), three of which we will briefly discuss.

First, it has been proposed that whenever change blindness occurs, representations of both pre- and post-change information must have been poor (Levin, Simons, Angelone, & Chabris, in press; O'Regan & Noe, in press). Recent studies have found support for this idea. In a real-world change detection task, in which the experimenter was surreptitiously replaced by another person (Levin et al., in press), subjects who detected the change correctly recognized both the pre- and post-change experimenters from a line-up, while subjects who

missed the change were at chance at both. However, if all instances of change blindness are due to poor pre- and post-representations, then even the most basic features are sometimes not represented sufficiently, since change blindness has been found even for features such as orientation and luminance (Rensink, 2000b). In the present study, we monitor the fate of orientation and size information in the 'one-shot' change detection paradigm.

A second possibility is that there may be a pre-change representation, but it is overwritten by the post-change representation (Beck & Levin, 2000; Becker, Pashler, & Anstis, 2000; Brawn, Snowden, & Wolfe, 1999; Tatler, 2001). The overwriting hypothesis is supported by evidence that memory for post-change objects is often more accurate than for pre-change objects (Beck & Levin, 2000; Brawn et al., 1999). Beck and Levin (2000) showed that memory for a pre-change object was poor even when the post-change display did not contain any object at that location: the pre-change object simply disappeared, and the entire display was slightly shifted in space. However, objects in the second display could have diverted attention away from the relevant object (O'Regan et al., 1999). Repeated search experiments indicate that the representation of an item after attention is diverted to something else (post-attentive vision) is indistinguishable from the pre-attentive representation (Wolfe, Klempen, & Dahlen, 2000). Brawn et al. (1999) showed that when attention is shifted towards an item, its immediate history is not recovered, contrary to what object-file theory (Kahneman & Treisman, 1984) would predict. When a target item was cued by an increase in its luminance and it changed color at the same time, subjects were at chance in naming the pre-change color of the target. Since the array of items was constantly visible, this suggests that the pre-attentive representation is easily overwritten (Brawn et al., 1999). In experiment 3, we tested the effect of shifts of attention during the interval of a change detection task on the pre-change representation.

The third option is that there are pre-change as well as post-change representations but that change blindness occurs due to limited capacity in comparing the two (Hollingworth & Henderson, 2002; Scott-Brown, Baker, & Orbach, 2000; Shore & Klein, 2000; Simons, Chabris, Schnur, & Levin, 2002). Angelone, Levin, and Simons (submitted for publication) provide evidence for a comparison failure by showing that observers who missed a replacement of the central actor across camera cuts in a brief movie-clip were above chance at recognizing the pre-change actor from a line-up. This indicates that having a pre-change representation sufficient for recognition does not guarantee successful change detection. Hollingworth and Henderson (2002) show that changes can be detected across many intervening eye movements but that detection depends on fixating the target object

before, as well as after the change. Therefore it was concluded that although durable representations are present, the comparison is only made upon re-fixation. Further evidence for the role of comparison comes from findings that spatial (Hollingworth, in press) and verbal (Simons et al., 2002) post-change cues can enhance change detection, in natural scenes. A post-change cue limits the comparison to a small part of the scene, rather than the entire scene. However, Becker et al. (2000) failed to find evidence for any advantage of a post-change cue in a very simple change detection task with a short interval and letters as stimuli. In the present study, we cued stimulus items before, during and after the interval between successive stimulus presentations. The cue after the interval is a post-change cue, which should enhance change detection if change blindness is due to a limit in the ability to compare.

In the present study, we monitored the fate of orientation and size information as a change detection trial progresses by cueing at varied moments during the trials. Experiment 1 shows that a considerable amount of information remains available for up to 1500 ms after offset of a pre-change display, but not after onset of the post-change display. Experiment 2 was done to investigate whether there would be a difference between using a gray or a white screen during the interval using a new group of subjects. We found no difference.

In experiment 3, we examined whether this representation would survive more than one shift of attention. Change blindness studies suggest that a diversion of attention may be detrimental to pre-change representations. It is commonly accepted that iconic memory does not survive saccadic eye movements, and recent evidence supports this (Tatler, 2001). However, saccades are also preceded by a shift of attention (McPeek, Maljkovic, & Nakayama, 1999). In most iconic memory studies, a single cue triggers a shift of attention towards a row of letters, but it is not known whether the readout of this information involves additional shifts of attention within the row. Further, shifts of attention take time (Duncan, Ward, & Shapiro, 1994), while the decay of iconic memory continues. Therefore, the stability of iconic memory across shifts of attention is not obvious. In experiment 3, a partial report cue was occasionally followed by a new cue, forcing subjects to select the first item, but then select another item (5°–8° away) in response to the new cue. The data indicate that the representation is not compromised.

In experiment 4, we tested whether a cue-advantage could be obtained when changes in either orientation or size could occur. Here, a cue can only be advantageous if the both the size and orientation of the same object are available in the representation, because subjects cannot predict which of these features will change. Becker et al. (2000) found that after 85 ms, cueing can recover enough information to support change detection, but not for identification of the original item. Without focused attention directed at the relevant item, it is thought that the representation rapidly dissolves to a level at which the features of different objects are easily confused (Rensink, 2000a). By the time attention arrives, it may be possible to find a single feature, but not two features bound within the same object. The outcome of our experiment, however, indicates that it is possible to retrieve either of the two.

2. General methods

2.1. Materials

The stimuli were presented on a 19 in. monitor using a PC, with a refresh rate of 60 Hz. Observers sat at a distance of about 39 in. such that the stimulus screen subtended about 16° by 21° of visual angle. Custom written software with MGL graphics libraries displayed the stimuli on the screen and recorded the type of trial, which button the subject pressed, whether the response was correct etc.

The stimulus displays consisted of textured fields in which eight rectangular figures were defined, either by line orientation (experiments 1–3) or dot color (experiment 4). The rectangles were placed on an imaginary circle with a radius of about 4° from the center of the screen, with a random jitter for each individual rectangle of between 0° and 1° towards the center or periphery. The orientation of each rectangle was either horizontal or vertical. The orientations were randomly assigned, with the precondition that each orientation should be used at least once in each display, to prevent displays in which all items had the same orientation. Throughout the trial, there was a red fixation point (0.18° in size) in the center of the screen. In the interval between successive stimulus presentations, the screen was gray in all experiments except in experiment 2, where one version of the task had a white screen during the interval. Average light intensity of the line orientation screens was 165 lx. There was no luminance difference between the figures and the background. Average light intensity of the dot colored screens was 140 lx, although in these displays there were small differences in luminance among figures and between figures and background due to differences in color. Light intensity of the gray screen was 75 lx, and the white screen was 255 lx.

A cue was presented to indicate which rectangle was likely to change. The cue was a yellow (experiments 1–3) or red (experiment 4) line, superimposed on the current image in the trial, placed in such a manner that one end was close to the fixation point (distance ≈ 0.7°) and the other end was close to the target rectangle (distance ≈ 0.7°). The length of the cue varied with the distance of the target rectangle, with an average of 2° of visual angle.

2.2. Procedure

Each trial a display with rectangular figures was presented for 500 ms ('stimulus 1'), followed by an interval, after which the display with the rectangles reappeared ('stimulus 2').

In 50% of all trials, in stimulus 2 one randomly chosen rectangle had changed orientation (experiments 1–3) or size (experiment 4). Stimulus 2 remained on screen until the subject pressed a mouse button to respond. As a button was pressed, subjects heard a high tone if the response was correct, and a low tone if the response was incorrect. Then the screen was green for about 1 s, before a new display of rectangles was shown. Interval durations were 400, 1000 and 1600 ms in the pilot experiment, 1600 ms in experiments 1–3, and 1500 ms in experiment 4.

Prior to the first session, the experimenter explained the task. In experiments 1–3, the subjects were instructed to detect whether any of the rectangles changed its orientation across the two presentations (horizontal to vertical or vertical to horizontal). Experiment 4 consisted of three different tasks with instructions to either detect changes in orientation, size, or both, depending on the task. They were told that 50% of all trials contained a change, and one rectangle would change at a time. Subjects responded by pressing a mouse button: right button if they thought there was a change, left button if they thought there was no change. They were informed that a cue would appear in most of the trials and that the cue meant 'If there is a change in this trial, it is the rectangle where the cue points at. If that rectangle does not change, there is no change in this trial'. The subjects were allowed 15 trials of practice, before beginning the first session.

2.3. Analysis

We used a method described by Pashler (1988) to express performance in terms of the number of items subjects have available for comparison, which we call 'capacity':

hit rate

$= $ capacity/number of figures

$+ ((\text{number of figures-capacity})/\text{number of figures})^*g$

where 'g' equals the false alarm rate. Thus,

capacity $= $ (hit rate $*$ number of figures

$-$ number of figures $*$ false alarm rate)/(1

$-$ false alarm rate)

This formula assumes that people hold on to a particular number of items (capacity), and answer 'yes' when one of them changes, while when there is no change

among those items, they answer 'no' or guess 'yes' in a certain proportion of trials (g), which is given by the false alarm rate. Like Pashler (1988) also admitted, this model may be crude in admitting no storage of partial information and attributing performance entirely to the maintenance, rather than the comparison process. However, it seems to provide a reasonable description of performance and corrects for guessing. This method has also been used by others (Luck & Vogel, 1997). We additionally analyzed the fraction of correct responses, sensitivity d' (Green & Swets, 1966), in experiment 1.

Paired t-tests were done to determine significant differences where necessary. All paired t-tests were 2-tailed, with $\alpha = 0.05$.

3. Experiment 1

A previous study has shown that an attentional cue can increase performance in a change detection/change blindness task (Becker et al., 2000). A cue was effective not only when given while the original stimulus was still present, but also 215 ms after the offset of original stimulus, namely in the interval between the original stimulus and the changed stimulus. In the present experiment, longer intervals were used, and the moment at which the cue appeared was varied.

Using the method described by Pashler (1988), we were able to estimate how many items subjects have available for comparison at different moments of cue presentation (capacity). This way we could get a better idea of what happens to the representation of objects from the moment the original stimulus disappears, throughout the interval and after the stimulus re-appears. In the condition where the cue appears while the original stimulus is still visible, it is not really justified to speak about 'memory capacity', because a capacity of 1 would be sufficient in that case. However, the crucial conditions in this experiment are those in which the cue appears during the interval, and in that case memory capacity does play a role. Capacity is used as a single measure for all conditions to be able to compare them.

In what we will refer to as the 'pilot', two observers were tested in three versions of the task which differed in the length of the interval (400, 1000 and 1600 ms). In the actual experiment, the 1600 ms version was tested in seven observers.

3.1. Methods

Participants: In the pilot, two experienced observers (VL and RL) were tested at three different interval durations. In the experiment, seven observers (three experienced, including one of the authors, four naïve) with normal or corrected to normal visual acuity took part.
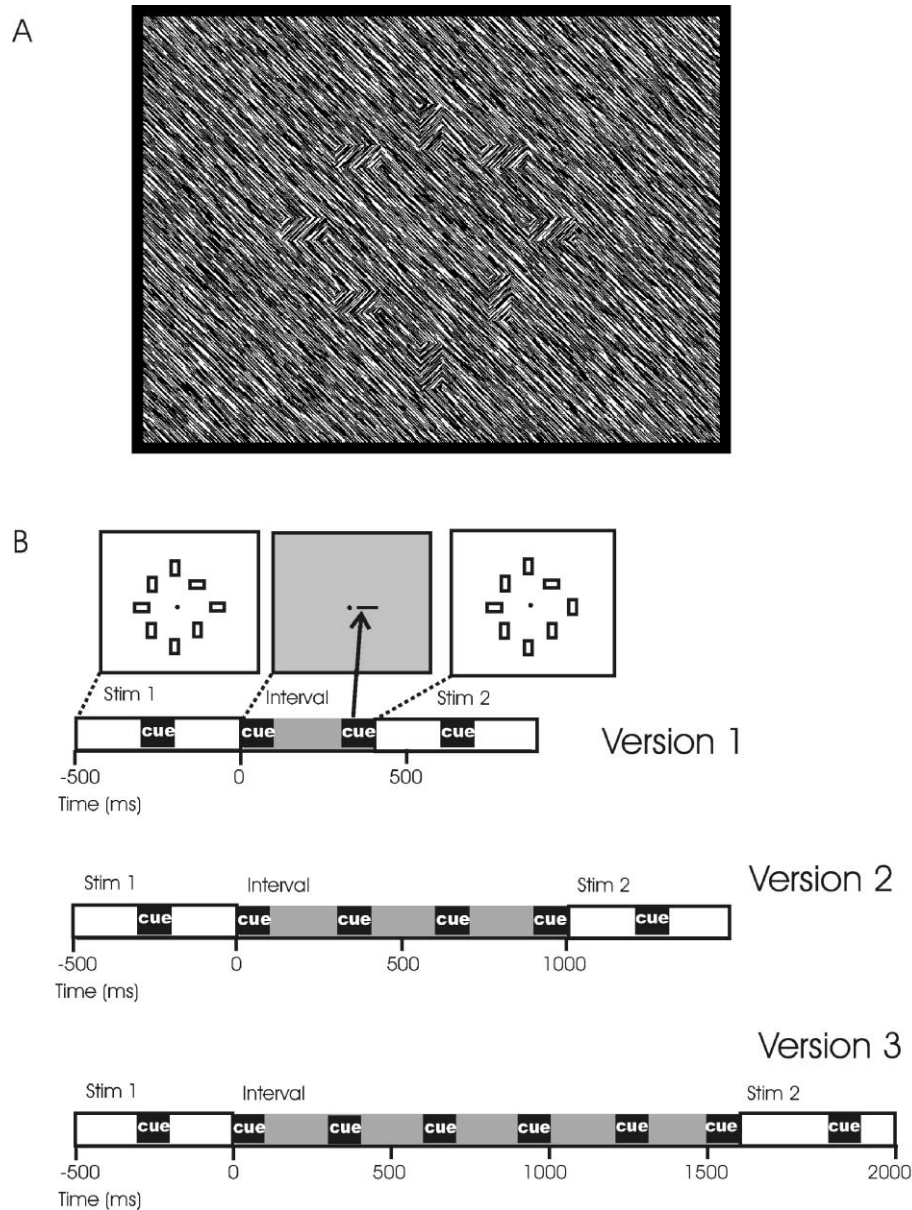
Fig. 1. (A) Example of a stimulus display used in experiments 1, 2 and 3; (B) schematic picture of the stimulus sequence in the pilot experiment (version 1, 2 and 3), and experiments 1 and 2 (version 3 was used in experiments 1 and 2). The moment at which the stimuli and cues are presented is indicated by their position on the long horizontal bar. The arrow shows an example of a cue appearing during the interval. On another trial, a cue could appear in stimulus 1 or stimulus 2. The black 'cue' labels on the time bars indicate the moments at which a cue could appear (duration: 100 ms). In the experiments, the cue was a yellow line. Each trial, one cue appeared at one time only, or there was no cue (no cue-condition). The cue was superimposed on what was on the screen at that moment. The three versions of the task differ in the length of the interval (400, 1000, and 1600 ms). Stimulus 1 was shown for 500 ms, then there was the interval, and finally stimulus 2 was shown. Stimulus 2 remained on screen until the observer responded. In the pilot and in experiment 1, the screen was gray during the interval. In experiment 2, one session contained a gray interval and the other session contained a white interval.

Materials: The stimulus displays consisted of black diagonal line segments on a white background, where most of the screen was filled with line segments of one orientation, except at the location of figures (rectangles), where the lines had the orthogonal orientation. The rectangles did not have an outline, but the texture discontinuity made them 'pop-out' from the rest of the texture (Bergen & Julesz, 1983), thus yielding the per-cept of rectangular figures on a background. The length of the line segments was about 0.5° of visual angle. All rectangles subtended 0.9° by 1.8° of visual angle. Fig. 1A shows an example of a stimulus display.

Procedure: In the pilot, there were three versions of the task, defined by the length of the interval.

In version 1, the interval was 400 ms. There were five conditions, defined by the timing of the cue, measured
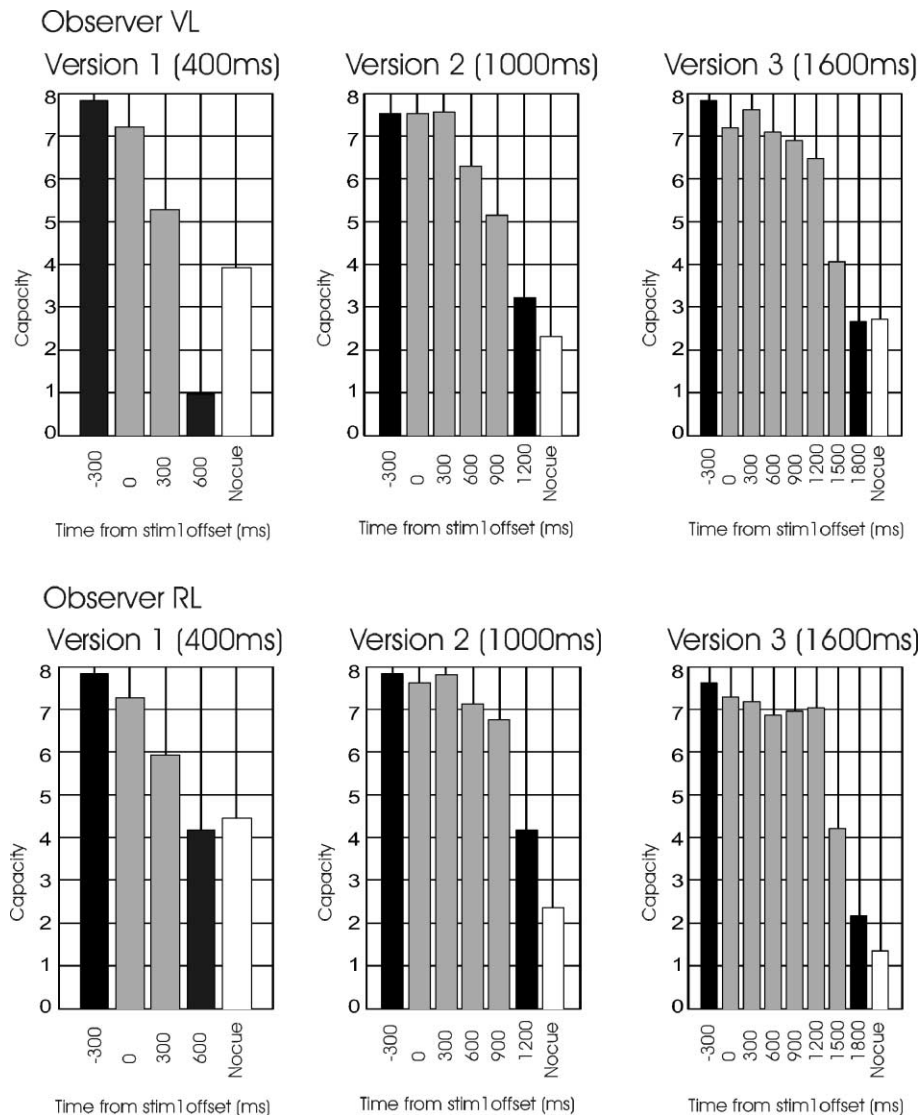
Fig. 2. Results of the pilot experiment. The outcome of the capacity measure is shown for each condition in the three versions (400, 1000 and 1600 ms interval) for both observers, VL (upper charts) and RL (lower charts). The labels on the *X*-axis indicate each condition by the time the cue appeared, measured from the offset of stimulus 1, as well as the no cue-condition.

from the start of the interval: −300; 0; 300; 600 ms, plus a condition with no cue. Thus, the cue at 600 ms appeared after the onset of stimulus 2 (the reappearance of the rectangles).

In version 2, the interval was 1000 ms. There were seven conditions, with a cue at: −300; 0; 300; 600; 900; 1200 ms, plus a condition with no cue. The cue at 1200 ms appeared after the onset of stimulus 2.

In version 3, the interval was 1600 ms. There were nine conditions, with a cue at: −300; 0; 300; 600; 900; 1200; 1500; 1800 ms, plus a condition with no cue. The cue at 1800 ms appeared after the onset of stimulus 2.

The main experiment was done with version 3 of the task. Subjects ran three sessions of 144 trials each. The number of change-/no-change trials per location and condition were balanced, but randomly mixed within

each session. Each condition contained 48 trials. A schematic picture of the conditions is shown in Fig. 1B.

3.2. Results

Pilot: The bar charts in Fig. 2 show the performance of the two observers in the pilot. The data from the three versions of the task have several aspects in common, in both observers: First, when no cue was given (white bars), the outcome of our capacity measure was 4.5 or less. Second, when the cue was given before the interval (left black bar in each chart), capacity was almost 8, indicating that the cue effectively improved change detection to almost perfect performance.

When the cue appeared during the interval (gray bars), capacity was higher than when no cue was given
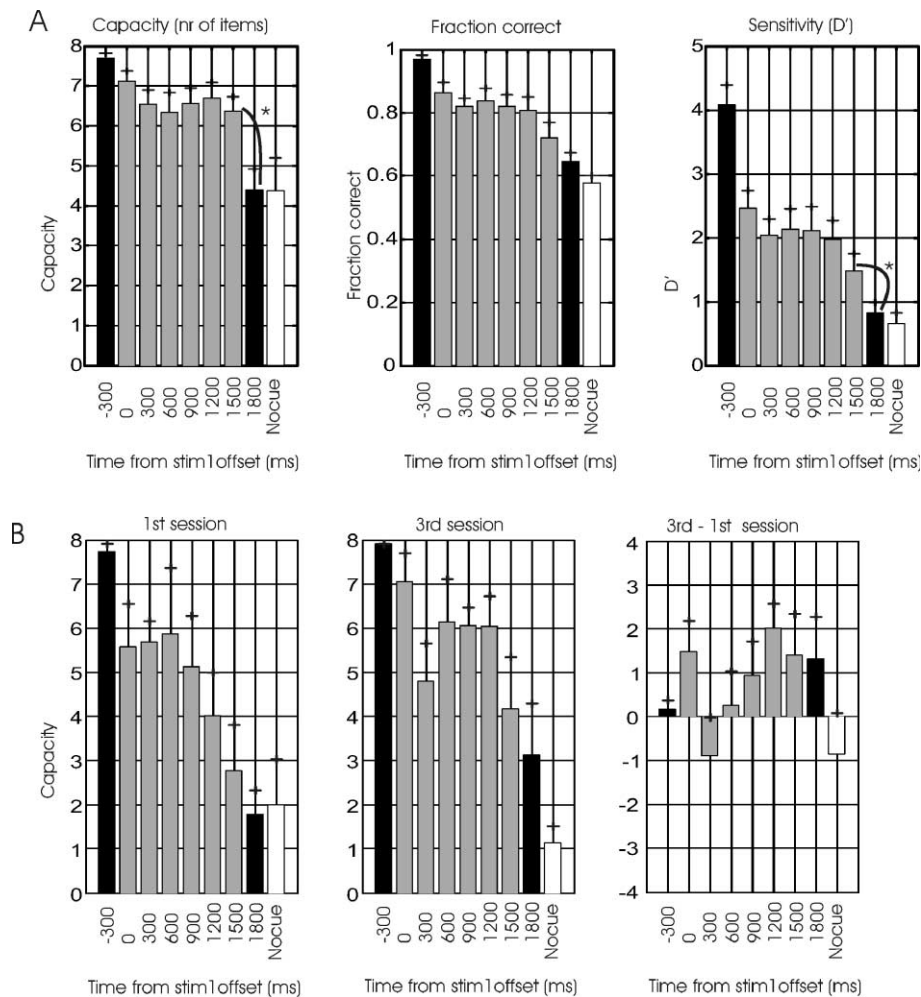
Fig. 3. (A) Results of experiment 1 ($n = 7$). Leftmost chart indicates the outcome of the capacity measure for each condition. The labels on the X-axis indicate each condition by the time the cue appeared, measured from the offset of stimulus 1, as well as the no cue-condition. The curve and asterisk indicate a significant difference ($p < 0.02$); middle chart shows the results of experiment 1 expressed as the fraction of correct responses for each condition; Rightmost chart shows the results of experiment 1 expressed as the sensitivity, d' (Green & Swets, 1966). The curve and asterisk indicate a significant difference ($p < 0.005$). (B) Capacity of naïve observers ($n = 4$) in first and third session of experiment 1. Leftmost chart is the first session, middle chart is the third session, and the rightmost chart shows the values of the third minus the first session. The labels on the X-axis indicate each condition by the time the cue appeared, measured from the offset of stimulus 1, as well as the no cue-condition. The difference shows that performance improved with experience. For a schematic representation of the stimulus sequence and conditions in this experiment, see Fig. 1 (version 3).

(white bars), although capacity did decrease during the interval in each version. Perhaps the most important observation is that capacity appeared to decrease as a function of time to stimulus 2 onset, rather than on time from stimulus 1 offset. For example, at the shortest interval (version 1), capacity with the cue at 300 ms was only slightly higher than in the 'no cue'-condition. With a longer interval (version 2), capacity at 300 ms was much higher in both observers. In version 2, capacity in observer VL has decreased by the time the cue appears at 900 ms, but with a longer interval (version 3), there was hardly any decrease at 900 ms. In both observers, capacity firmly decreased when the cue appeared just before the onset of stimulus 2 in all three versions of the task. Mixed results were found when the cue was given after the interval (right black bar in each chart). Here,

capacity was not always higher then when no cue was given.

Experiment: Task version 3 was tested in seven subjects. The leftmost chart in Fig. 3A presents subjects' average capacity in each of the nine conditions. The results were similar to those observed in the pilot. When no cue was given (white bar), capacity was about 4. When the cue was given before the interval (left black bar), capacity was almost 8, indicating that the cue effectively improves change detection to almost perfect performance. When the cue appeared during the interval, it remained effective. Despite some decrease during the first 600 ms, capacity remained above 6. However, when the cue appeared after the onset of stimulus 2 (at 1800 ms), capacity was again about four items. A paired t-test indicated no significant difference between

'cue-after-stimulus-2' and the no cue-condition ($t(12) = 0.004$, $p = 0.99$). When the cue appeared 1500 ms after offset of stimulus 1, capacity was still significantly higher than when the cue appeared after the onset of stimulus 2 ($t(12) = 3.02$, $p < 0.02$). The same tendency can be observed in the 'fraction correct' responses (middle chart Fig. 3A), and the sensitivity, d' (rightmost chart Fig. 3A). Although d' was considerably lower when the cue appeared in the interval than when it appeared before the interval, d' was still significantly higher with a cue at 1200 ms than with a cue after the onset of stimulus 2 ($t(12) = 3.44$, $p < 0.005$). The criterion value β (Green & Swets, 1966) was positive for all conditions, with a peak level of 0.97 for the condition with the cue at 1500 ms, except when the cue appeared before the interval (-0.2), indicating a bias favoring 'no-change' responses in most conditions. Some learning took place over the course of the three sessions, as indicated by the data of the inexperienced observers' first and third session (see Fig. 3B). The increase in performance is especially pronounced for 'late cues', with the strongest increase at 1200 ms within the interval (approximately two extra items in terms of capacity).

3.3. Discussion

The results from the pilot experiment indicate that cueing can improve change detection even when the cue appears during the interval between successive images, as predicted by findings of Becker et al. (2000). Although the estimated number of retained items decreases during the interval, this decrease appears related to time from stimulus 2 onset rather than to time from stimulus 1 offset. This suggests that the decrease in the number of items in the representation of items is due to interference, rather than decay.

The results of this experiment indicate that people have a large capacity representation of a stimulus (more than four items) for at least 1500 ms after it has disappeared. This representation can be used to detect a change when the stimulus reappears, when cued before the onset of stimulus 2. When no cue appears, only four items remain available to detect a change, which is in accordance with previous estimates (Luck & Vogel, 1997). The cue-advantage may result from a fragile, but large capacity memory store co-existing with working working memory, perhaps similar to iconic memory. In response to the cue, subjects may transfer the target item from iconic memory to the more durable working memory, so as to protect it against interference from stimulus 2 (Becker et al., 2000; Gegenfurtner & Sperling, 1993). Like Becker et al. (2000), we found that post-change cueing was useless, indicating that limiting the comparison to only one object after the change does not improve change detection. This argues against the hypothesis that change blindness is due to failed com-

parisons (Hollingworth, in press; Hollingworth & Henderson, 2002; Scott-Brown et al., 2000; Shore & Klein, 2000; Simons, 2000; Simons et al., 2002). However, most of the evidence for post-change cue-advantage involve natural(istic) scenes, whereas our study and that of Becker et al. (2000) used abstract figures and letters not embedded in a natural environment. Natural scenes and natural objects may allow subjects to make a high level representation, abstracted from metric visual detail. This type of representation may be more stable (Hollingworth, in press). A more parsimonious explanation, however, is that the representation of our artificial stimuli strictly involves sensory memory, which is apparently more easily erased, as also suggested by iconic memory studies (Sperling, 1960).

A remarkable aspect of our findings is that the cue remains advantageous for such a long time: 1500 ms, considerably longer than the estimated duration of iconic memory (Sperling, 1960). It cannot be argued that this is due to lower light intensity in the interval (75 lx) than the stimuli (165 lx). A strong luminance contrast *between figures and background*, (such as black letters on a white background) would have produced a long lasting after-image of the figures when followed by a dark interval (Averbach & Sperling, 1961; DiLollo & Bischof, 1995). In our stimuli, there was no luminance difference between the figures and the background, therefore the duration of the after-image left behind by the figures was negligible. Nevertheless, in experiment 2 we rule out a contribution of light intensity by a direct comparison between a white and a gray interval screen in a new group of subjects.

Practice with the task apparently increases performance and increases subjects' ability to take advantage of the cue, which is in accordance with suggestions from another study with partial report (Chow, 1985). Inexperienced subjects may not shift attention to the cued item fast enough to protect the item against interference by stimulus 2. However, even in naive subjects doing the task for the first time, capacity at 1200 ms into the interval is two points higher than the no cue-condition. In contrast, in most iconic memory experiments, partial report performance decays to whole report level within 500 ms (Averbach & Sperling, 1961; Sperling, 1960).

4. Experiment 2

In the previous experiment, iconic memory remained available throughout the 1500 ms interval. However, it could be that the light intensity of the interval plays a role in the decay time of the memory trace. Averbach and Sperling (1961) showed that the duration of iconic memory increases as the luminance of the post-stimulus screen decreases. In the previous experiment, we used a gray interval screen. A white screen (stronger light

intensity) may yield a stronger decay. In the next experiment, a new group of observers did two versions of the task, to check whether a strong light intensity during the interval yields a lower capacity compared to a low light intensity during the interval. Seven observers, who did not join the previous experiment, did one session of the task with a gray interval, and one session with a version in which the screen during the interval was white.

4.1. Methods

Participants: Seven observers (one experienced, six naïve). All observers had normal or corrected to normal visual acuity.

Materials: There were two versions of the task, identical to the task in the previous experiment (version 3), except that in one version, the screen during the interval was white.

Procedure: The interval duration (1600 ms) and conditions (9) were identical to the task in experiment 1 (Fig. 1B, version 3). Subjects ran one session of 144 trials on each version of the task. The order in which the task versions were tested was mixed across subjects.

Analysis: Capacity measures (experiment 1) were used to evaluate performance. Paired *t*-tests for each condition were done to test for differences between capacity when the interval was white and capacity when the interval was gray. Additionally, paired *t*-tests within each version of the task were done to test for differences between conditions with cue and the no cue-condition. All paired *t*-tests were 2-tailed.

4.2. Results

The bar charts in Fig. 4 present subjects' average capacity for each version of the task, and the difference between the two versions. There were no significant differences between the two versions for any condition (rightmost chart). Although capacity decreased as the cue delay increased, the difference with the no-cue condition was still significant at 1200 ms after stimulus offset in both versions of the task (paired *t*-test ['cue 1200 ms' vs 'no cue'], gray version: $t(12) = 3.25$, $p = 0.007$; white version: $t(12) = 2.87$, $p = 0.014$). Although the cue still appeared to be effective after stimulus 2 onset, the differences with no cue did not reach significance (paired *t*-test ['cue 1800 ms' vs no cue], gray: $t(12) = 1.31$, $p = 0.21$; white: $t(12) = 1.61$, $p = 0.13$).

4.3. Discussion

The purpose of experiment 2 was to test whether capacity with a cue during the interval would be lower when the interval screen is white, compared to when the interval screen is gray, as in the first experiment. We found no significant differences between the two versions of the task, indicating that the luminance of the interval screen cannot account for the effect we reported in experiment 1.

Overall performance in this experiment was lower than in experiment 1. However, the present experiment only consisted of a single session per task version, while in experiment 1, subjects ran three sessions. Further, in
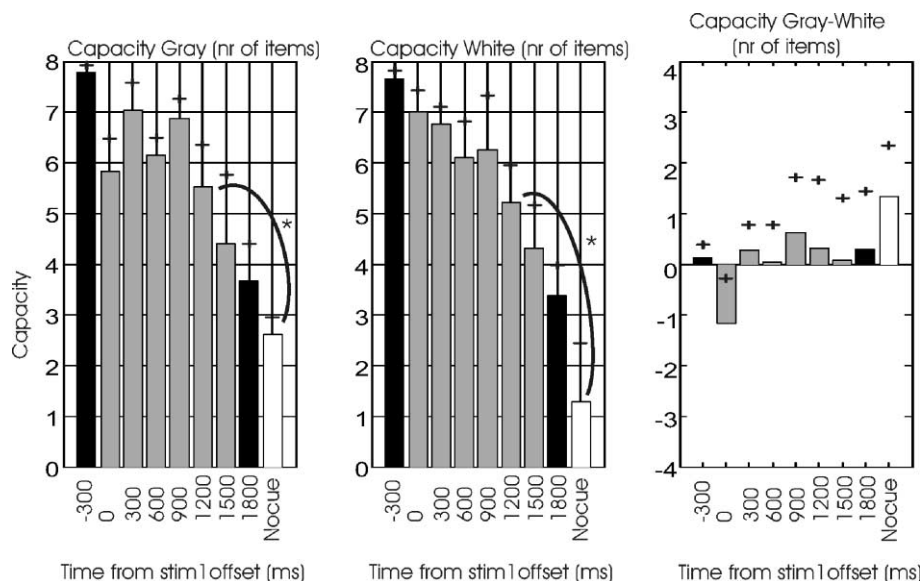
Fig. 4. Results of experiment 2 (new group of observers, $n = 7$). Average capacity for each version of the task (left, gray interval; middle, white interval; right, gray minus white). There were no significant differences between the two versions for any condition (rightmost chart). The curve and asterisk indicate significant differences (gray: $p = 0.007$; white: $p = 0.014$). Conditions were identical to experiment 1, except that the luminance of the interval screen was different in the task with the white interval. For a schematic representation of the stimulus sequence and conditions, see Fig. 1 (version 3).

the present experiment, six out of seven subjects were naive, while in experiment 1, five out of seven subjects were naïve.

Compared to typical iconic memory studies, decay in our experiments is slow. This can perhaps be explained by a difference in paradigms. In our experiments, subjects only have to press a button to indicate whether the stimulus is same or different, whereas in the typical iconic memory experiment, subjects have to verbally identify items, which takes time and could in itself interfere with recall (Coltheart, 1980; Sperling, 1960). Further, Becker et al. (2000) showed that a cue supports change detection up to a later stage in the interval than identification of the pre-change item, indicating that more information is required for identification than for change detection. Further, in iconic memory studies, stimuli are usually letters (Coltheart, 1980; Sperling, 1960), whereas we used rectangular figures and subjects had to detect changes in just one basic feature: orientation.

5. Experiment 3

Experiment 1 showed that after an image disappears, there is a representation of the orientation of almost all items in a display. This representation can be accessed and used for change detection when attention is cued to the appropriate item. But what happens to the other items in memory after such a shift of attention is executed? It has been proposed that spatially and temporally coherent representations only exist within the current focus of attention. Thus, once the focus of attention has shifted to one of the items, the representation of other items may 'dissolve' (Rensink, 2000a; Wolfe, 1999). Most change blindness studies use manipulations such as strong luminance transients to divert attention. This may be detrimental to pre-change representations. Moreover, in studies using successive stimulus presentations, the stimuli themselves may include components that attract attention and thereby compromise the pre-change representation. Saccades are known to wipe out iconic memory, however, the role of attentional shifts in this respect is not known, since iconic memory experiments usually include only one cue for items which are grouped in a matrix.

In the present experiment, a cue was always presented during the interval. However, some trials contained two cues (condition 3). Subjects were told that whenever they saw a second cue, that second cue was the 'real' cue. Because the conditions were randomly mixed, one could not predict whether a given trial would contain one or two cues. We controlled for the possibility that subjects postponed their shift of attention to wait for a possible second cue, by including condition 2, in which stimulus 2 appeared earlier. Postponing an attentional shift

would then lead to low performance in that condition, because the item would not be selected in time before the appearance of stimulus 2.

5.1. Methods

Participants: In this experiment, the same subjects took part as in experiment 1, at the same day. Sessions of each experiment were intermingled. The same materials were used.

Procedure: The procedure was roughly the same as in experiment 1, except that now there were four conditions. The time from the start of the interval (or the offset of stimulus 1) for the presentation of the cues and the changed stimulus were varied, in addition to the presence of a 'fake' cue. Condition 1: cue at 400 ms, changed image at 1000 ms; condition 2: cue at 400 ms, changed image at 1600 ms; condition 3: fake cue at 400 ms, real cue at 1000 ms, changed image at 1600 ms; condition 4: Cue at 1000 ms, changed image at 1600 ms. A schematic picture of the conditions can be seen in Fig. 5A.

In condition 3, (with the fake cue), the fake cue looked exactly like a real cue. With real cue we mean that it was the only useful cue in the same sense as in experiment 1 and in the other conditions. The fake cue pointed at an item that would not change. On the imaginary circle of items, there was always at least one item between the item cued by the real cue and the one cued by the fake cue. Subjects were given the same basic instruction, with the addition that whenever they saw a second cue, that cue would be the real cue. Each subject ran three sessions of 68 trials each. The number of change-/no-change trials per location and condition were balanced, but these different types of trial were presented in a random fashion. Each condition contained 48 trials per subject.

Analysis: Capacity measures (experiment 1) were used to evaluate performance. Paired *t*-tests were done to determine whether performance is worse when the real cue is preceded by a fake cue (condition 3) than when only the real cue is presented at the same moment in time (condition 4). If uncued items are lost, condition 3 should be worse. Condition 2, in which stimulus 2 appeared early to control for postponement of the attentional shift, was compared to condition 1, where stimulus 2 appeared later.

5.2. Results

The bar chart in Fig. 5B presents subjects' average capacity in each of the four conditions. Condition 3 (with the fake cue) and condition 4 are not significantly different, indicating that the fake cue did not make the real cue less effective ($t(12) = 0.26$, $p = 0.8$). Capacity in condition 2 is not significantly different from condition 1

A

B

Fig. 5. (A) Schematic picture of the stimulus sequence in experiment 3. The procedure was roughly the same as in experiment 1, except that now there were four conditions. For the sake of clarity, the stimulus sequence is represented by a separate time bar for each condition. The critical condition in this experiment was condition 3, in which two cues were presented. Condition 3 was identical to condition 4 except that the real cue was preceded by a fake cue pointing at another item. Except for its non-validity, the fake cue looked exactly like a normal cue; (B) results of experiment 2. The outcome of the capacity measure for each condition. The labels on the X-axis indicate each condition. There are no significant differences. An example of a stimulus display used in this experiment is shown in Fig. 1A.

($t(12) = 0.12$, $p = 0.9$). It is also not lower than comparable conditions in experiment 1 (conditions 3 and 4), indicating that subjects did not postpone a shift of attention awaiting a possible second cue ([cond 2, expt 3] vs [cond 3, expt 1] $t(12) = 0.12$, $p = 0.9$; [cond 2, expt 3] vs [cond 4, expt 1] $t(12) = 0.39$, $p = 0.69$). Capacity in conditions 1 and 2 is slightly higher than conditions 3 and 4 (not significant: cond 1 vs cond 3 $t(12) = 1.40$, $p = 0.18$; cond 1 vs cond 4 $t(12) = 1.70$, $p = 0.11$; cond 2 vs cond 3 $t(12) = 1.22$, $p = 0.24$; cond 2 vs cond 4 $t(12) = 1.44$, $p = 0.17$). This is possibly because the (real) cue appears earlier in conditions 1 and 2. Criterion value β was positive for all conditions (minimum: 0.08 condition 1; maximum 0.60 condition 2), indicating a bias favoring 'no-change' responses.

5.3. Discussion

The results of this experiment indicate that cueing subjects to shift attention to an item in memory does not render other items unavailable. Therefore, this memory does not require focal attention to be maintained. Apparently, one can freely pick items from the existing representation and save them into a more durable store without losing yet unchosen items.

It has been proposed that the representations only remain coherent within the focus of attention, which implies that the representation of unattended information should become worse very rapidly (Rensink, 2000a). Iconic memory studies would also predict a strong decrease in the number of available items

between 400 ms (first cue) and 1000 ms (second cue) after stimulus offset (Sperling, 1960). However, the two cues in our experiment were 600 ms apart and there was no significant decrease in capacity during that time.

Our results do make sense in respect to other recent findings. Using a variation on the repeated search paradigm, Wolfe and Brawn (submitted for publication) show that after an item has been attended and attention is shifted to another item, subsequent changes to the previously attended item are not noticed. When the item is hidden and subjects are asked to name the color of that item, subjects mention the color it had when it was attended. Thus, the representation of items may be maintained across shifts of attention, but is not updated when changes occur outside the focus of attention. Investigations by Hollingworth, Williams, and Henderson (2001) even show that changes can be detected after observers make several intervening eye movements, and hence shifts of attention, indicating that information must have been maintained.

6. Experiment 4

Experiments 1 and 2 showed that there is a large capacity representation of the orientation of items in a display. We wanted to know whether this representation is just a collection of single features or whether binding has taken place. This tells us more about the level of processing at which this representation is made. In search tasks, searching for targets defined by single features is independent of the number of distractors, whereas targets defined by conjunctions of features take longer to be found as more distractors are present. This marks the difference between 'pre-attentive' and 'attentive' processing respectively (Wolfe, 1996). Processing of conjunctions requires binding of features that belong to a single object. Repeated search experiments show that search for changes in color-orientation pairings is inefficient, and remains inefficient even after extended exposure (Wolfe, Oliva, Butcher, & Arsenio, 2002). This is in support of the idea that pre- and post-attentive vision consists of an unbound soup of basic features (Treisman & Gelade, 1980; Wolfe et al., 2000). Luck and Vogel (1997) estimated the capacity of working memory using a change detection task. They found a capacity of four items when people were detecting changes in color, but also when they were detecting changes in size *or* color. Therefore, they concluded that the capacity of working memory, which they think was the crucial factor in their task, must be understood in terms of integrated objects rather than individual features (Luck & Vogel, 1997).

In the present experiment we showed subjects rectangles of different sizes and orientations. To test the representation during the interval for conjunctions, we randomly mixed trials in which a rectangle changed size with trials in which a rectangle changed orientation. One could argue that '*either* size *or* orientation' is not a conjunction, but disjunction. However, in order to make use of the cue during the interval in that condition, people must select both size and orientation of the same object in order to know whether one of them has changed in stimulus 2. The type of representation we investigate may support the retrieval of orientation information, but not orientation and size of the same object. We mixed sessions of this 'conjunction task' with sessions containing only size changes or sessions containing only orientation changes. The displays were constructed from colored dots instead of line segments. The rectangles within each display could have different colors, to minimize grouping based on size or orientation.

6.1. Methods

Participants: Seven observers who did not take part in the other experiments, except one author (three experienced, four naïve) with normal or corrected to normal visual acuity took part in the experiment.

Materials: The basic materials used in this experiment were the same as in experiment 1. However, in this experiment, the stimulus displays consisted of dots on a white background. The rectangles were defined by a difference in the color of the dots with respect to the surrounding dots, which were gray. Within each display, each rectangles could be composed of red, yellow, blue or green dots. In this experiment, the rectangles could have two sizes: big (0.9° by 1.8°) or small (0.6° by 1.2°). The colors and sizes were randomly assigned, with the precondition that each color and each size should be used at least once in each display. The cue in this experiment was a red line instead of a yellow one.

Procedure: The basic procedure was identical to experiment 1, except that in this experiment, the gray interval lasted 1500 ms. Sessions with only orientation changes ('orientation task'), only size changes ('size task') and both size and orientation changes ('conjunction task') were mixed. In the orientation task, subjects were instructed to judge whether any of the rectangles changed its orientation across the two presentations (horizontal to vertical or vertical to horizontal). In the size task, they were instructed to judge whether any of the rectangles changed in size across the two presentations. In the conjunction task, they were instructed to judge whether any of the rectangles changed in either size or orientation. The conjunction task contained an equal number of size changes as the number of orientation changes, and they were randomly mixed. In trials in which there was a change, it was either a size change or an orientation change.

Each task had three conditions based on the time at which the cue was presented. Cue-times in ms from the

start of the gray interval (or offset of stimulus 1) were −300, 700 or 1600. At 1600 ms, the cue came 100 ms after the onset of stimulus 2. A schematic picture of the conditions can be seen in Fig. 6A. For each task, subjects ran three sessions of 96 trials. The number of change-/no-change trials per location and cue-time condition were balanced, but these different types of trial were randomly mixed. Because each task had three conditions, each condition contained 96 trials per subject. In the conjunction task, each condition contained an equal number of size and orientation changes.

6.2. Results

The bar charts in Fig. 6B show the results for the orientation task, the size task and the conjunction task. In each task, capacity is highest when the cue is given in advance and worst when given after the appearance of stimulus 2, like in experiment 1. A cue during the

interval (condition 2) yields a higher score on our capacity measure than a cue after the interval (condition 3) in each task (paired *t*-tests orientation $t(12) = 2.37$, $p < 0.05$; size $t(12) = 2.18$, $p < 0.05$; conjunction $t(12) = 2.51$, $p < 0.05$). Capacity after the interval (rightmost bar in each graph) is not significantly lower in the conjunction task than in the other two tasks (conjunction vs size $t(12) = 0.89$, $p = 0.38$; conjunction vs orientation $t(12) = 1.99$, $p = 0.07$). Capacity during the interval in the conjunction task is not significantly different from the same condition in the other two tasks (conjunction vs size $t(12) = 0.33$, $p = 0.74$; conjunction vs orientation $t(12) = 1.72$, $p = 0.1$).

6.3. Discussion

The results of experiment 3 show that after an image disappears, the representation that remains available contains not only the orientation of the objects that were
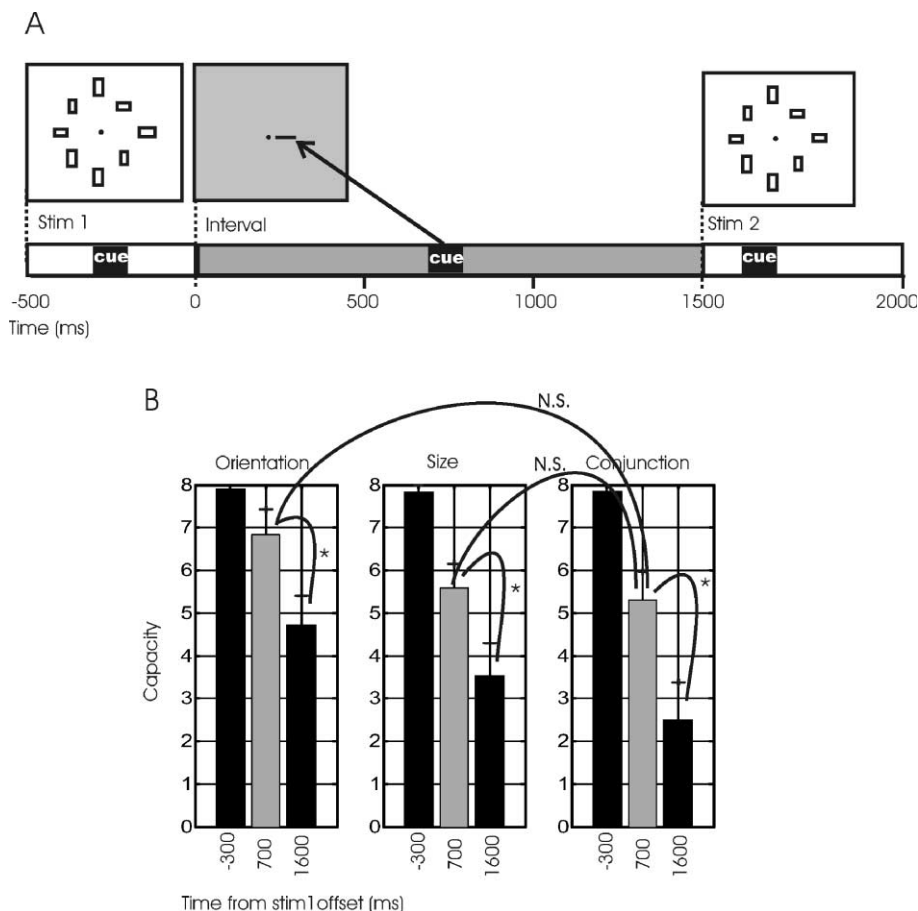

Fig. 6. (A) Schematic picture of the stimulus sequence in experiment 4, which was identical for the orientation, size and conjunction task. Each task had three conditions defined by the timing of the cue. The moment at which a cue could appear is indicated by the position of the short 'cue' labels on the long horizontal bar. The arrow shows an example of a cue appearing during the interval. On another trial, a cue could appear in stimulus 1 or stimulus 2 as indicated by the labels on the long horizontal bar. (B) Results for the 'orientation', the 'size', and the 'conjunction' task of experiment 3. The outcome of the capacity measure is shown for each condition. The labels on the *X*-axis indicate each condition by the time the cue appeared, as measured from the offset of stimulus 1. The bent curves indicate the comparisons that were made. Asterisks indicate significant differences (see text for details). NS = non-significant.

in it, but also their size. In the conjunction task, when the cue appeared during the interval, stimulus 2 had not yet appeared, so the subjects could not know at that point whether a change in size or orientation would occur. Therefore, in order to take advantage of the cue, they must have taken both the size and orientation of the same object and put it in a more durable store like working memory, to make the comparison after appearance of stimulus 2. Apparently, subjects can get that combined information from the representation for as many items as they have available when looking for a change in only one dimension.

7. General discussion

The present experiments were done to further characterize the memory for a visual image shortly after it has disappeared. In the first experiment we showed that this memory has a high capacity and it remains intact for at least 1200 ms, and 1500 ms in experienced observers. This memory can be used to improve change detection performance if the location where a change is likely to occur is cued before the image reappears, supporting findings of Becker et al. (2000). Our second experiment shows that the luminance of the interval screen does not influence the cue-advantage. The third experiment showed that attention can be shifted to one item within the representation, without reducing the availability of other items. The fourth experiment shows that the cue-advantage is not limited to changes in orientation, but can also be found for size changes. Moreover, when it is unpredictable whether a change will involve orientation or size, the cue-advantage is still found. This indicates that the representation must contain information about which features belong to which object.

These results support findings that four items or less are available for comparison *after* a change has occurred (Luck & Vogel, 1997; Pashler, 1988; Rensink, 2000a), but that there is a representation of more pre-change items before the stimulus re-appears. A number of items may be overwritten or masked by the onset of the new stimulus, in this case the reappearance of the rectangles (Beck & Levin, 2000; Becker et al., 2000; Brawn et al., 1999; Tatler, 2001). Although our use of the cue is very similar to the partial report method in iconic memory studies (Coltheart, 1980, 1983), our results indicate that information for change detection remains available for a longer period than the estimated decay time of iconic memory.

One alternative to account for the large memory capacity we find is 'grouping'. Since the orientation (or size, in expt 4) of the items was randomized, some displays could have many items of the same orientation. Items of one type may be grouped to form one 'chunk'

of information. The configuration of each display was not recorded, therefore we cannot rule this out. The method we used to determine memory capacity assumes independent memory for each item, but if grouping is a factor, 'large capacity' could mean either a lot of simple things or a few more complicated ones. However, we did put one constraint on randomization to prevent grouping, namely that no display could contain only items of one type (e.g. all horizontal). Further, even when memory during the interval was coded as groups of items rather than individual items, our main effect remains, namely that capacity during the interval is larger than after the interval.

Like Becker et al. (2000), we found that cueing after change occurrence is useless. This argues against the possibility that change blindness in this paradigm is due to a limit in the 'capacity to compare' (Hollingworth & Henderson, 2002; Scott-Brown et al., 2000; Shore & Klein, 2000; Simons et al., 2002). Cueing after reappearance greatly simplifies the comparison, because it becomes unnecessary to compare the entire array: one just has to compare one rectangle with how it looked before. However, our results have shown that in that condition, change detection does not improve over getting no cue at all. As discussed in experiment 1, the type of stimuli we used may play a role. Natural scenes may allow subjects to make a high level representation, abstracted from metric visual detail, which is fairly stable (Hollingworth, in press), whereas for our artificial and meaningless stimuli, subjects are not inclined to make such high level abstractions.

The present data agree with the presence of two parallel types of short term memory (Baddeley, 1986; Coltheart, 1983; Phillips, 1974). Almost all items enter the first type of memory. It is like iconic memory, because it has a high capacity and it is maskable (Coltheart, 1983; Sperling, 1960). The second type of memory is one that resists interference by new stimuli. When new items enter the visual system, they replace the old items, except the ones that have entered the second type of representation. A maximum of about four items can simultaneously be in that state. This is usually called working memory (Baddeley, 1986; Luck & Vogel, 1997), or short term memory (Phillips, 1974). The cue-advantage arises because the subjects selectively transfer the cued item from iconic memory to the more durable working memory (Coltheart, 1983; Gegenfurtner & Sperling, 1993; Sperling, 1967).

Although the pre-change representation is easily overwritten by new visual input, it is clear from our results that not all new input is capable of doing that. The gray screen was not enough, the white screen was not enough, and shifts of attention did not have any influence either. Given the independence from attention, it is important to know that we found evidence that representation contains information about more than one

feature of the same object. This may indicate that even feature conjunctions remain available. However, our stimuli were not *unattended*. During stimulus presentation, attention was likely to be divided over the screen. Further, there is evidence that certain feature conjunctions are available very early in visual processing (Holcombe & Cavanagh, 2001; Theunissen, Alain, Chevalier, & Taylor, 2001; Woods, Alain, & Ogawa, 1998).

With regard to the neural basis of the effects we observed, the working memory component is very likely to involve the prefrontal cortex and infero-temporal cortex (IT). Both areas contain cells (at least in the monkey) that selectively increase their firing rate when an item has to be remembered during a brief interval (Baylis & Rolls, 1987; Fuster, 1973; Goldman-Rakic, 1990; Miller, Erickson, & Desimone, 1996; Miller, Li, & Desimone, 1993). However, activity during the interval in IT cortex is disrupted by intervening stimuli (Baylis & Rolls, 1987; Miller et al., 1993). This suggests that some IT cells are more involved in iconic memory than in working memory.

It has been proposed that area IT serves two parallel short term memory mechanisms, one automatic, non-selective and one that selectively encodes the relevant stimuli (Miller & Desimone, 1994), which is compatible with our interpretation of the present results. Cells in more posterior brain areas, like V4, V2 and V1, are not commonly associated with memory, but recently, memory-related activity has been found in V1. The memory signal involved was not an enhancement of firing rate during the interval, but a continuation of figure–background activity after stimulus disappearance (Supèr, Spekreijse, & Lamme, 2001). It becomes increasingly evident that many different brain areas are simultaneously involved in various kinds of short term memory (Cornette, Dupont, Bormans, Mortelmans, & Orban, 2001). Therefore, the transfer of information from iconic to working memory should probably not be seen as moving a representation from one brain area to another, but rather as a local increase in connectivity between areas.

Acknowledgements

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