Research Article

Feature Bindings Are Maintained in Visual Short-Term Memory Without Sustained Focused Attention

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Abstract. Does the maintenance of feature bindings in visual short-term memory (VSTM) require sustained focused attention? This issue was investigated in three experiments, in which memory for single features (i.e., colors or shapes) was compared with memory for feature bindings (i.e., the link between the color and shape of an object). Attention was manipulated during the memory retention interval with a retro-cue, which allows attention to be directed and focused on a subset of memory items. The retro-cue was presented 700 ms after the offset of the memory display and 700 ms before the onset of the test display. If the maintenance of feature bindings – but not of individual features – in memory requires sustained focused attention, the retro-cue should not affect memory performance. Contrary to this prediction, we found that both memory for feature bindings and memory for individual features were equally improved by the retro-cue. Therefore, this finding does not support the view that the sustained focused attention is needed to properly maintain feature bindings in VSTM.

Keywords: visual attention, visual short-term memory, visual working memory, binding

Extensive evidence suggests that the binding of visual features into unified objects requires focused attention (see, e.g., Cohan & Rafal, 1991; Eglin, Robertson, & Knight, 1989; Friedman-Hill, Robertson, & Treisman, 1995; Humphreys, 2001; Treisman, 1999; Treisman & Gelade, 1980; Treisman & Schmidt, 1982). For instance, according to Treisman and Gelade's (1980) influential Feature Integration Theory, the sequential allocation of focused attention to areas of space allows the features of a given object to be bound through their shared location. The role of focused attention in the maintenance of the feature bindings in visual short-term memory (VSTM), however, is currently being debated, and the literature reflects conflicting opinions about this issue.

On the one hand, some studies have suggested that sustained focused attention is necessary to actively maintain the link between features of an object in VSTM, just as attention is required to bind visual features in perception (Rensink, 2000; Stefurak & Boynton, 1986; Wheeler and Treisman, 2002; Wolfe, 1999). We call this the *focused attention hypothesis*. According to this view, once attention is withdrawn from an object, the representation of the object in memory collapses into its constituent features, leaving memory for the features potentially intact but substantially degrading memory for their correct associations. For instance, in a series of change detection tasks in which observers looked for changes between two successive visual displays, Wheeler and Treisman (2002) compared a *binding condition* with a *feature condition*. In the binding condition, all the features (i.e., shapes and colors) from the memory display were presented again at test, but they were paired anew on some occasions. Successful change detection in that condition thus required observers to memorize the binding information, that is, information about which shape was associated with which color. In the feature condition, the value of two features simply changed at test. Memory for the features was required in the feature condition, but not memory for the feature bindings. Two different kinds of test displays were also used. In the *Whole-Display test*, all memory items were presented at test, whereas in the *Single-Probe test*, only one item was shown. It was found that performance in the binding condition was worse than performance in the feature condition only with whole-display tests. Wheeler and Treisman concluded that the maintenance of feature bindings in memory requires sustained focused attention, and that the occurrence of a new, attention-demanding visual input, such as a whole-display test, disrupted attention to the bindings.

Contrary to this proposal, other studies hold that whereas visual features are bound into object representations through focused attention at the perceptual level, these representations remain bound in VSTM without requiring any additional resources beyond those required to maintain individual features (Hollingworth & Henderson, 2002; Irwin, 1992; Johnson, Hollingworth, & Luck, 2008; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). We call this the *unfocused attention hypothesis*. Congruently, Luck

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and Vogel (1997) have suggested that the capacity of VSTM is set by the number of integrated objects that can be stored and that it is independent of the number of features within each object (for important restrictions of these results, see Delvenne & Bruyer, 2004, 2006; Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002). Luck and Vogel (1997) found that memory capacity for objects defined by a single feature (e.g., color or orientation) was similar to capacity for objects defined by multiple features (e.g., a bar that varied in size, orientation, color, and the presence or absence of gaps). Implicit in this is the notion that once feature bindings are properly computed at the perceptual level, they remain intact in memory even in the absence of sustained focused attention. A similar proposal was recently formulated by Johnson et al. (2008). In a change detection study, the authors compared memory for bindings with memory for features when a subsequent visual search task that required sequential shifts of spatial attention was completed during the delay interval. It was found that both memory for bindings and memory for features were equally impaired by the search task. These results suggest that although an attention-demanding secondary task can disrupt VSTM, attention does not play a special role in the maintenance of the feature bindings *per se* (see also Allen, Baddeley, & Hitch, 2006; Gajewski & Brockmole, 2006).

In this study, the role of focused attention in the maintenance of feature bindings in VSTM was directly tested by pitting the focused and unfocused attention hypotheses against each other. Our approach consisted of manipulating attention during the memory retention interval of a change detection task using the *retro-cue paradigm*, where the to-be-changed memory item is cued during the retention interval of the memory task (for studies using the retro-cue paradigm, see, e.g., Griffin & Nobre, 2003; Lakha & Wright, 2004; Landman, Spekreijse, & Lamme, 2003, 2004; Lepsien, Griffin, Delvin, & Nobre, 2005; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura, Luck, & Vecera, 2007). Cuing attention in memory to the potential target has been found to increase change detection performance. In Landman et al. (2003), for example, a centrally presented arrow that pointed at the location of one of the memory items was delivered during the retention interval of the memory task. The arrow (i.e., the cue) informed participants about which item would later be probed. The results showed that, compared with no-cue trials, retrospectively cuing an item in VSTM significantly increased change detection performance, even when the cue was presented at relatively long intervals (i.e., 1,500 ms) after the offset of the memory display. The retro-cue allows attention to be directed and focused on one location during the retention interval. Once attention is focused on one location, memory for the items falling in that location is solidified and interference from the test display is eliminated. In contrast, without focused attention memory has been found to be highly vulnerable to interference (see Chun & Potter, 1995). According to the focused attention hypothesis outlined above, feature bindings are maintained in VSTM through sustained focused attention. Therefore, memory for bindings should not benefit from a retro-cue. The unfocused attention hypothesis, however, suggests that features bindings can be maintained in VSTM without continued focused attention, just like individual features. As a result, memory for features and memory for bindings should benefit equally from a retro-cue.

This study is thus focused on the retro-cue benefit in comparing memory for features and memory for bindings. A change detection paradigm was used in which a briefly presented memory display of six items was followed by a test display consisting of a single item.[1] The task was to decide whether the single item in the test display was one of the six memory items. The memory items were defined either by a single feature (i.e., shape *or* color – *shape* and color *conditions*) or by two features (i.e., shape *and* color – *binding condition*). Importantly, in the binding condition, the features shown in the test display were always present in the memory display, but they were paired anew on some occasions (see Wheeler & Treisman, 2002, for a similar procedure). Because such a change was defined as a switch between the colors (or, equivalently, between the shapes) of two stimuli, participants had to memorize the binding information, that is, information about which shape was associated with which color throughout the task in order to avoid making incorrect associations. It was therefore impossible to accomplish the task simply by recovering the features independently. The focused attention hypothesis predicts that because memory for feature bindings already requires sustained focused attention, it will not benefit from the retro-cue. As a result, the retro-cue benefit will occur in the feature (i.e., shape and color) conditions only. The unfocused attention hypothesis, however, predicts that because the feature bindings can be maintained in memory in the absence of sustained focused attention, they will benefit from the retro-cue. As a result, the retro-cue benefit will occur equally in both the feature and binding conditions.

Experiment 1

Method

Participants

Fourteen naïve undergraduate students from the Université Libre de Bruxelles (ULB) took part in the study. All

[1] The change detection paradigm requires, by definition, that aside from the change all the items from the first display are presented again at test (i.e., *whole-display test*). In this study, however, only one item was presented at test (i.e., *single-probe test*). The rationale for using a single-probe design here was to prevent relational coding from influencing the results (Delvenne & Bruyer, 2006; Jiang, Olson, & Chun, 2000) and spatial memory from assisting performance (Simons, 1996). Yet, we still use the term "change detection" as this term has been used in many previous studies using single-probe test displays (e.g., Delvenne & Bruyer, 2004; Olson & Jiang, 2002, 2004; Wheeler & Treisman, 2002).

had normal (self-reported) or corrected-to-normal visual acuity and normal color vision.

Apparatus

In all the experiments of this study, visual stimuli were generated by a 2.8 GHz PC and displayed on a screen with a refresh rate of 60 Hz. The scripts for the experiments were generated by E-Prime programming software (Psychology Software Tools, Inc. E-mail www.pstnet.com/eprime) and responses were collected using the computer keyboard.

Materials and Procedure

Eight different simple shapes (Figure 1) and eight colors (black, blue, green, pink, red, turquoise, white, and yellow), produced by permutation of the presence (255 on the 0–255 scale) or absence (0 on the 0–255 scale) of red, green, and blue phosphor, were used as stimuli. At a viewing distance of 60 cm, the stimuli subtended a visual angle of approximately 0.81° × 0.81°. Each memory display consisted of six stimuli that were randomly positioned at six different possible locations on an imaginary circle with a radius of about 2.86° from the center of the screen (5.72° × 5.72° of visual angle). The six locations were the 12, 2, 4, 6, 8, and 10 o'clock locations. A gray background (127 on the 0–255 scale of red, green, and blue phosphors) was used throughout the experiment to reduce afterimages.

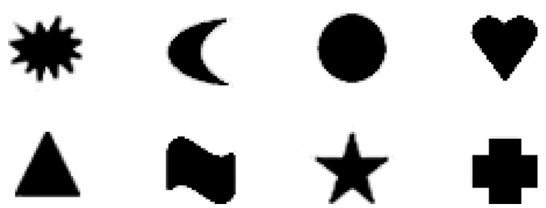

Figure 1. Shapes used in this study.

On each trial, participants were shown a central fixation point (a small white square subtending 0.1° × 0.1° of visual angle at viewing distance of 60 cm) that remained on the screen throughout the entire trial. After 500 ms, the memory display was presented for 500 ms, followed by a 1,500 ms blank interstimulus interval (ISI), and then by the test display, which remained present until a response key was pressed. The test display consisted of a single stimulus at the center of the screen. Participants were instructed to indicate, as accurately as possible, whether that stimulus had been present in the memory display (with 50% probability). As soon as the participants had responded, feedback was given for 500 ms as either a happy green smiley for a correct response, or a sad red one for an incorrect response. The next trial was automatically initiated 1,000 ms later.

There were three conditions: shape, color, and binding conditions (Figure 2). In the *Shape Condition*, the memory display consisted of six different shapes that were all colored in white. Participants were instructed to memorize the shapes and to decide whether the shape of the single stimulus at test had been present in the memory display. When a change occurred, the stimulus at test was of a new shape not previously presented in the memory display. In the *Color Condition*, the memory display consisted of six circles that were all in different colors. Participants were instructed to memorize the colors and to decide whether the color of the single stimulus at test had been present in the memory display. When a change occurred, the stimulus at test was of a new color not previously presented in the memory display. In the *Binding condition*, the memory display consisted of six different colored shapes. Participants were instructed to memorize both the shapes and the colors and to decide whether the relationship between the shape and the color of the single stimulus at test had been preserved from the memory to the test display. When a change occurred, the stimulus at test was always of a shape and of a color previously presented in the memory display, but the relationship

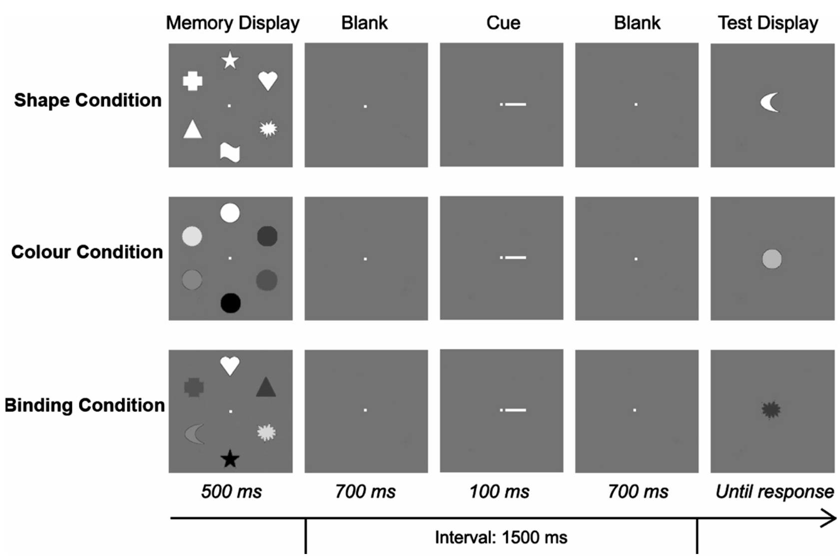

Figure 2. Illustrations of the three conditions and the time course used in Experiment 1. In the uncued trials, the memory and test displays were separated by a 1,500 ms blank interval, whereas in the cued trials, a spatial cue was displayed for 100 ms framed in two 700 ms blank intervals. The different gray levels represent different colors.

between shape and color was different, so that the stimulus at test had the shape of one stimulus from the memory display and the color of another (that had been presented adjacent to the first one in the memory display).

In half of the trials, a cue was displayed for 100 ms in the middle of the blank ISI that separated the memory from the test display, namely 700 ms after the offset of the memory display. The cue was a white line subtending 1° × 0.1° of visual angle. One of its ends was very close to the fixation point (0.1° of visual angle) and its other end pointed to a between-stimuli location, that is, a location situated between two stimuli. The two stimuli that were located on both sides of the cue were the two targets. The rationale for cuing two stimuli instead of only one was to prevent participants from maintaining the two features of a single cued object independently in the Binding Condition. The necessity of storing binding information only occurs when more than one integrated object is present. Therefore, by cuing two objects, participants not only had to encode and maintain in memory the two colors and the two shapes that had been cued, but they were also to remember which color went with which shape.

Participants were explicitly told that the single central stimulus at test could be merely compared with the two targets. They were informed of the fact that the cue was 100% valid, that is, that a change would always involve the cued stimuli. Participants were tested individually in a quiet room with dim lighting. At the beginning of the experiment, a detailed description of the task was provided. Trials were blocked by both condition (color, shape, and binding conditions) and by cuing (cued vs. uncued trials), with block order counterbalanced across participants. Each block consisted of 12 practice trials and 48 experimental trials. As a result, the present experiment consisted of a total of 288 experimental trials (i.e., 3 [conditions] × 2 [cuing] × 48 cases). At the end of each block, participants were given their percentage of correct responses. This, according to most of the participants, was rather effective in inducing them to perform better on the next block.

Results and Discussion

For the uncued trials, the percentages of correct responses were 59.4, 77.5, and 63.7, in the shape, color, and binding conditions, respectively. For the cued trials, the percentages of correct responses were 72.5, 83.6, and 70.8 in the shape, color, and binding conditions, respectively. Figure 3 shows the estimated memory capacity (k) in each condition. Memory capacity (k) was calculated using a formula introduced by Pashler (1988) and later refined by Cowan (2001): capacity (k) = N(hit rate + correct rejection rate − 1). Hit rate was defined as accurate change detection; correct rejection

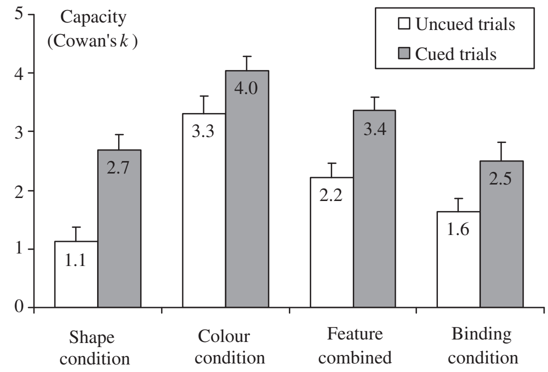

Figure 3. Results of Experiment 1 with estimated memory capacity as a function of presence or absence of the cue and conditions. Error bars represent standard errors of the mean values. Note that the Feature Combined condition represents the averaged capacity from the Shape and Color conditions.

rate was defined as the proportion of trials where participants correctly answered "no, there is no change". N represents the total number of stimuli in the memory display. This method has been also used in a number of previous visual memory studies (e.g., Vogel, Woodman, & Luck, 2006; Xu & Chun, 2006). We calculated the estimated memory capacity separately for each condition and for each participant. We also conducted analyses on log-transformed percentage correct for each experiment. Log-transformed percentage correct produced the same pattern of statistical significance as k in all experiments.

A condition (Color − Shape − Binding) × Cuing (cued vs. uncued trials) ANOVA (repeated measures) on estimated capacity (k) revealed a main effect of condition, $F(2, 26) = 66.081$, $MSE = 0.401$, $p < .001$, a main effect of cuing, $F(1, 13) = 34.831$, $MSE = 0.669$, $p < .001$, with higher capacity when the cue was present, but no interaction ($p = .174$). As Alvarez and Cavanagh (2004) previously found, memory capacity can vary substantially across different types of stimuli. Pairwise comparisons revealed indeed that although capacity in the shape and that in the binding conditions did not differ ($p = .34$), it rose significantly in the color condition compared to the two others ($p < .001$).[2]

The current experiment revealed a striking retro-cue benefit on change detection performance, so replicating previous retro-cue studies (e.g., Landman et al., 2003; Makovski et al., 2008): When a cue indicating which memory item will need to be compared at test was displayed after the offset of the memory display, participants' ability to make their judgments was greatly improved compared to a situation where no cue was presented. In addition, the

2 Given that six colors and six shapes were sampled from a set of eight colors of eight shapes, one may suggest that participants could have performed the task by noting which two colors or shapes were absent from the arrays. This would have been a useful strategy, especially in the feature conditions (although this pattern was also observed by Johnson et al., 2008, in the absence of this potential strategy). However, the use of such a tactic would have predicted an absence of a retro-cue benefit, at least in the feature conditions. Indeed, it is likely that a similar amount of attentional resources is required for recollecting the two missing features and for focusing attention on two features from the memory array. In addition, such a strategy cannot explain why only the color condition, but not the shape condition, was performed better than the binding condition.

magnitude of the retro-cue benefit was similar in both the feature and binding conditions: memory capacity increased by 54.54% on average in the feature conditions compared to 56.25% in the binding condition. This provides clear evidence against the *focused attention hypothesis*, which would have predicted that only memory for single features can benefit from the retro-cue if memory for bindings requires sustained focused attention. In contrast, our finding supports the *unfocused attention hypothesis*, which postulates that feature bindings, just like individual features, can be maintained in memory even in the absence of sustained focused attention, and may thus benefit from the retro-cue. This suggests that a similar amount of attentional resources is allocated for the maintenance of single features and integrated objects in short-term memory. For both types of stimuli, initial attention can be shifted from an unfocused to a focused mode of attention on a subset of memory items during the ISI and enhance their representation and robustness to interference.

Experiment 2

A second experiment was designed to control two factors that may have contributed to the retro-cue benefit observed in Experiment 1. First, the time during which all the items from the first display had to be maintained in memory diverged between the cued and uncued trials. The memory items had to remain stored and accessible for the entire ISI (i.e., 1,500 ms) in the uncued trials, but only for the first 700 ms in the cued trials, after which only the two cued items could be retained for the remainder of the ISI. It is therefore possible that such timing dissimilarities across trials have contributed to the effect observed in Experiment 1. In that context, the retro-cue benefit would be better explained in terms of memory decay rather than in terms of resilience to interference (for a similar hypothesis, see Makovski et al., 2008). Second, the number of memory items to be compared at test also differed between the cued and uncued trials. In the cued trials, the test stimuli had to be compared to the two cued items, whereas in the uncued trials, it had to be compared to all six memory items. If confirmed, this would suggest that the retro-cue benefit must be understood in terms of simplification of the comparison process (for a similar hypothesis, see Matsukura et al., 2007).

To address this in Experiment 2, we reduced the ISI from 1,500 to 700 ms in the uncued trials, while keeping it at 1,500 ms in the cued trials, thus making the two conditions comparable insofar as the time during which all the memory items had to be maintained is concerned. In addition, in order to match the number of comparisons to be made at test across the two conditions, the test stimulus was displayed between the locations previously occupied by two memory items rather than at the center of the screen. Participants were explicitly instructed to compare the test stimulus with either the two cued items (in the cued trials) or with the two memory items that had previously been displayed on either side of the test stimulus (in the uncued trials). Crucially, in both conditions, it is now the case that only two items have

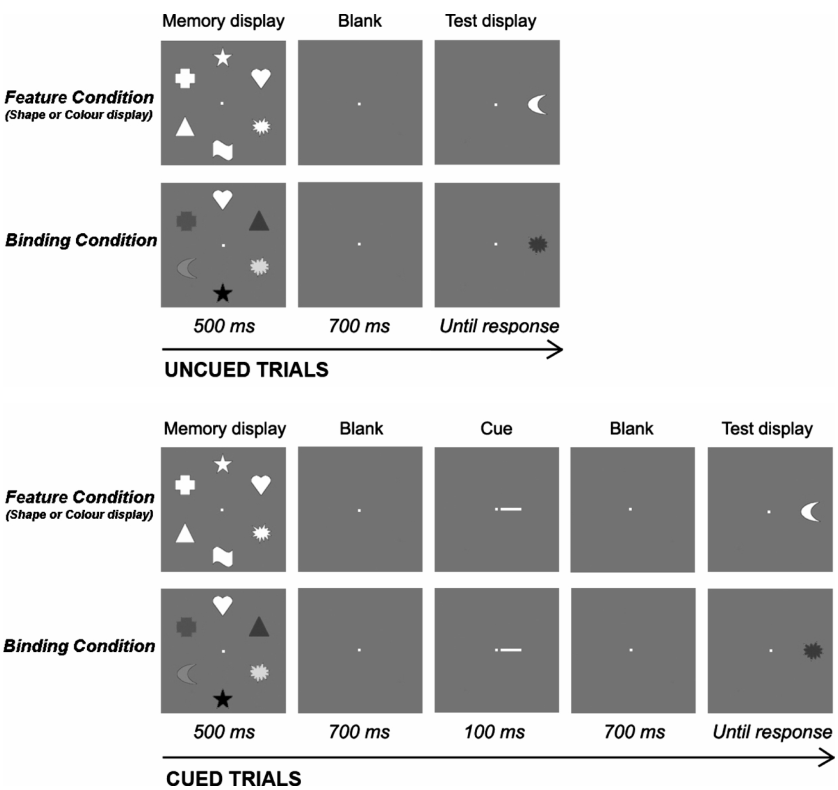

Figure 4. Illustration of the trial types used in Experiment 2. In the uncued trials, the memory and test displays were separated by a 700 ms blank ISI, whereas in the cued trials, a spatial cue was displayed for 100 ms framed in two 700 ms blank ISI. In addition, the test stimulus was located in-between two memory items. The different gray levels represent different colors.

to be recollected from memory for these comparisons to be possible (see Figure 4).

Method

Participants

Fourteen naïve undergraduate students from ULB participated in the study. All had normal (self-reported) or corrected-to-normal visual acuity and normal color vision.

Materials and Procedure

This experiment replicated Experiment 1 with the following changes: (i) the ISI in the uncued trials was reduced to 700 ms, while that in the cued trials remained at 1,500 ms; (ii) the single probe at test was located between the two memory items that had to be compared, as described above; and (iii) the color and shape displays were randomly mixed within a single feature condition. Trials were blocked by conditions (feature vs. binding condition) and by cuing (cued vs. uncued trials), with order counterbalanced across participants. Each block consisted of 12 practice and 48 experimental trials. As a result, this experiment involved a total of 192 experimental trials (i.e., 2 [memory display types] × 2 [cuing] × 48 cases).

Results and Discussion

For the uncued trials, the percentages of correct responses were 71.4% and 61.9% in the feature and binding conditions, respectively. For the cued trials, the percentages of correct responses were 80.1% and 67% in the feature and binding conditions, respectively. We observed the same general pattern of results as in Experiment 1 (Figure 5). A condition (feature vs. binding condition) × Cuing (cued vs. uncued trials) ANOVA (repeated measures) on estimated memory capacity (k) revealed a main effect of condition, $F(1, 13) = 63.53$, $MSE = 0.406$, $p < .001$, with higher capacity in the feature condition, a main effect of cuing, $F(1, 13) = 18.92$, $MSE = 0.499$, $p < .001$, with higher capacity when the cue was present; but no interaction ($p = .516$). Memory capacity increased by 38.4% and by 42.8% in the feature and binding conditions, respectively.

These results show that when the cued and uncued conditions are matched according to (1) the duration of the ISI during which all six items from the first display need to be maintained in memory and (2) the number of comparisons that need to be made at test, retro-cuing still improves change detection performance and memory capacity in both the feature and binding conditions. Thus, neither the timing dissimilarities across conditions, nor the capacity limits involved in comparing two views can explain the retro-cue benefit observed in Experiment 1.

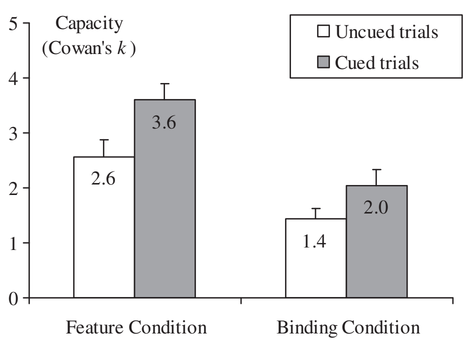

Figure 5. Results of Experiment 2 with estimated memory capacity as a function of presence or absence of the cue and conditions. Error bars represent standard errors of the mean values.

Experiment 3

In a final experiment, the role of iconic memory in the observed cuing effect was tested. Iconic memory (or *sensory persistence*) upholds an accurate, preattentive, high-capacity, maskable, retinotopic sensory representation of the visual input (Averbach & Coriell, 1961; Gegenfurtner & Sperling, 1993; Neisser, 1967; Sperling, 1960). The duration of iconic memory is commonly thought to last less than half a second (cf. Chow, 1986). After this short period of time, the information is lost unless it has been transferred into the more durable VSTM. The results from previous cuing studies (Gegenfurtner & Sperling, 1993; Sperling, 1960) indicate that attention plays an important role in transferring the information to VSTM. Even if the retro-cue used in this study was presented 700 ms after the offset of the memory array, that is, at a point in time when any iconic representation is likely to have faded (e.g., Chow, 1986), the possibility that some lasting residual iconic traces may have contributed to the cuing effect must be ruled out. In order to ensure that the retro-cue directed and focused attention on memory items that were already transferred in VSTM, a mask was presented between the offset of the memory display and the onset of the cue. The mask was assumed to overwrite any iconic representations that were not already stored in VSTM.

Method

Participants

Fourteen naïve undergraduate students from ULB participated in the study. All had normal (self-reported) or corrected-to-normal visual acuity and normal color vision.

Materials and Procedure

This experiment replicated Experiment 2 with the following changes: (i) a mask consisting of six squares made of

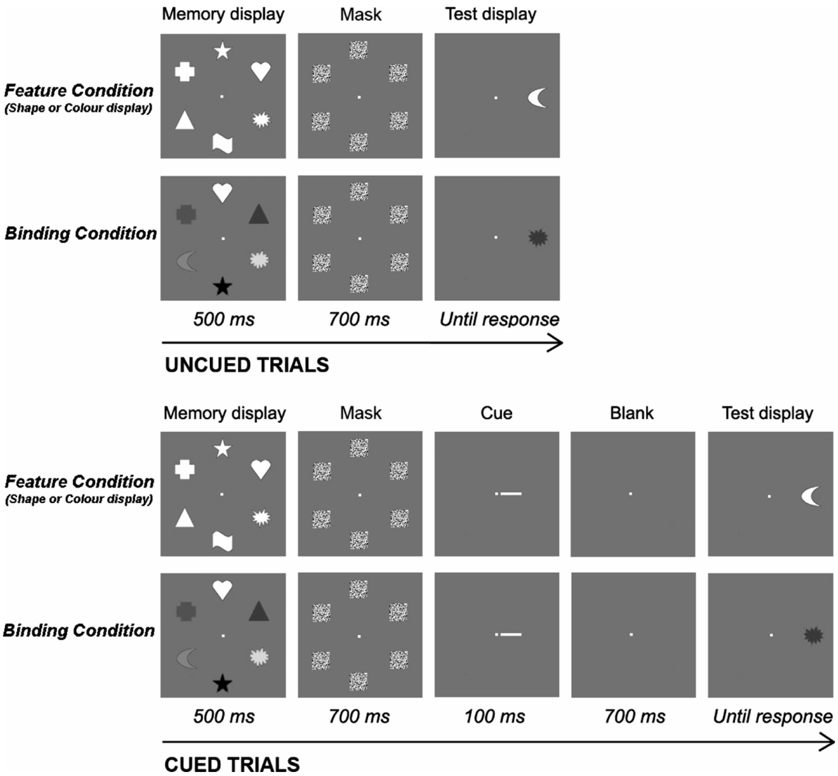

Figure 6. Illustration of the trial types used in Experiment 3. A visual mask was presented for 700 ms after the offset of the memory display. The different gray levels represent different colors.

randomly mixed colors and located at the same locations as the memory items was presented for 700 ms after the offset of the memory display (Figure 6) and (ii) the participants were instructed to memorize two digits at the beginning of each trial and to recall them at the end of it. This verbal memory task was used to prevent the participants from adopting verbal strategies (see, Baddeley, 1986).

Results and Discussion

For the uncued trials, the percentages of correct responses were 68.8% and 59.5% in the feature and binding conditions, respectively. For the cued trials, the percentages of correct responses were 71.4% and 63.8% in the feature and binding conditions, respectively. In all conditions, the percentage of correct recalls of the two digits was superior to 95%. As shown in Figure 7, the same pattern of results as Experiments 1 and 2 was observed. The condition (feature vs. binding condition) × Cuing (cued vs. uncued trials) ANOVA (repeated measures) on estimated memory capacity (k) revealed a main effect of condition, $F(1, 13) = 20.512$, $MSE = 0.891$, $p < .002$, with higher capacity in the feature condition, a main effect of cuing, $F(1, 13) = 7.677$, $MSE = 0.595$, $p < .02$, with higher capacity when the cue was present; but no interaction ($p = .263$). Memory capacity increased by 31.8% and by 33.3% in the feature and binding conditions, respectively. These findings reveal a retro-cue benefit in both the feature and binding conditions despite the presence of a mask during the ISI. Therefore the retro-cue benefit in this study cannot be explained by a privileged

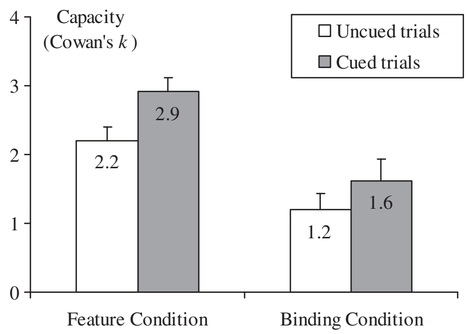

Figure 7. Results of Experiment 3 with estimated memory capacity as a function of presence or absence of the cue and conditions. Error bars represent standard errors of the mean values.

transfer of the cued items from iconic to VSTM. Rather, by directing attention on some items in VSTM, the retro-cue allows memory to consolidate and the cued items to become more resistant to interference.

General Discussion

In this study, the question of whether sustained focused attention is required to maintain feature bindings in VSTM was investigated. Focused attention is assumed to play a major role at the perceptual level when multiple features need to be bound together into an object (Treisman &

Gelade, 1980). It is however currently uncertain whether the maintenance of feature bindings in VSTM requires sustained focused attention. Some studies suggest that feature bindings need focused attention to be properly maintained in memory (Rensink, 2000; Stefurak & Boynton, 1986; Wheeler & Treisman, 2002; Wolfe, 1999), whereas other studies have indicated that the bindings can be maintained in VSTM in the absence of focused attention (Hollingworth & Henderson, 2002; Irwin, 1992; Johnson et al., 2008; Luck & Vogel, 1997; Vogel et al., 2001).

Here, we directly tested this issue using the retro-cue paradigm in a change detection task, where the to-be-changed memory item is cued after the offset of the memory display (Griffin & Nobre, 2003; Lakha & Wright, 2004; Landman et al., 2003, 2004; Lepsien et al., 2005; Makovski & Jiang, 2007; Makovski et al., 2008). The retro-cue allows attention to be directed and focused on a portion of memory items. By focusing attention on those memory items, memory strengthens and the cued items become more resilient to interference. A direct consequence of this is the observation of an increase in change detection performance (see Makovski et al., 2008).

Here, we found the retro-cue benefit to be equivalent both in feature (shapes or colors) and binding conditions. The feature conditions required the maintenance in VSTM of individual features only, whereas the binding condition required the maintenance of the link between features of an object. If feature bindings, but not individual features, are maintained in VSTM through continued focused attention, only the feature conditions should have benefited from the retro-cue. Indeed, if attention is already focused on the memory items, cuing the items during the ISI would be of no use. Contrary to this prediction, we found that both memory for features and memory for bindings benefited equally from the retro-cue. This equivalence strongly suggests that feature bindings are stored in VSTM without requiring any attentional resources beyond those required to maintain single features.

Note that memory capacity for bindings was generally lower than memory capacity for individual features. This may appear to be inconsistent with the pattern of results observed by Wheeler and Treisman (2002). The authors found that accuracy in a binding condition with a single-probe test was not significantly different from accuracy in a feature condition. In this study, Experiment 1 revealed that memory capacity for bindings was lower than memory capacity for colors but equivalent to memory capacity for shapes. Because both types of features are included in the binding condition, it is reasonable to expect that the level of performance in the binding condition would match the one from the most difficult feature condition. Nonetheless, a direct comparison between memory for features and memory for bindings may not be entirely sensible. A judgment based on the association of two features may in general be more difficult than the one based on a single feature value. What is important here, however, is that the retro-cue does not enhance memory capacity for features more than it does enhance memory capacity for bindings.

One issue that remains to be addressed is whether attention can be focused on more than one memory items simultaneously. If focused attention recruits all attentional resources available, only a single memory item may be attended at a time. By contrast, if additional attentional resources can operate on top of focused attention, it may be possible for multiple memory items to be attended simultaneously. In this study, we did find a benefit from retro-cuing concurrently two memory items. The retro-cue that we used pointed to a location in-between two memory items, therefore focusing attention to two items at the same time. This finding appears to be inconsistent with the results of a recent study by Makovski and Jiang (2007) in which a retro-cue benefit was found only when attention focuses on a single memory item. Using either two peripheral cues or one central cue pointing to two diagonal locations, Makovski and Jiang failed to find an advantage provided by those cues on memory performance. One possible explanation that may reconcile those apparently contradictory findings is that only one location can be cued in memory, regardless of the number of items falling within that location. The cue used in this study pointed to one location that included two adjacent memory items, whereas the cues used in Makovski and Jiang's (2007) study pointed to two distinct locations. Clearly, further research will be needed to test this possibility, and more generally, to examine the limitations of orienting attention in memory.

To sum up, this study provides further support to the view that sustained focused attention is not required to maintain feature bindings in VSTM. Attention may play a more general role in VSTM than that of binding and maintaining the links between the features of an object.

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