Indirect assessment of visual working memory for simple and complex objects

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Previous research has shown that visual search performance is modulated by the current contents in visual working memory (VWM), even when the contents of VWM are irrelevant to the search task. For example, visual search is faster when the target—rather than a distractor—is surrounded by a shape currently held in VWM. This study uses the modulation of visual search by VWM to investigate properties of VWM. Participants were asked to remember the color or the shape of novel polygons whose “goodness” of figure varied according to Garner’s (1962) rotation and reflection transformation principle. During the memory retention interval, participants searched for a tilted line among vertical lines embedded inside colored polygons. Search was faster when the target—rather than a distractor—was enclosed by the remembered polygons. The congruity effect diminished with increasing memory load and decreasing figure goodness. We conclude that congruity effects in visual search can indirectly assess VWM representation strength.

Many everyday tasks require us to buffer visual information for a few seconds after its disappearance. For example, when crossing a busy street, we must look left and right and remember momentary traffic conditions before deciding to cross. In team sports, players often need to remember the positioning of teammates and opponents in order to determine their next movement. The brief buffering and manipulation of visual information relies on visual working memory (VWM): an online memory that is important for maintaining temporal continuity. In the laboratory, VWM is often operationally defined by performance in a short-term, change-detection task in which observers judge whether two visual displays separated by a few seconds of retention interval are the same or different (Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974; Rensink, 2002). Using this procedure, researchers have found that the capacity of VWM is no more than three or four objects (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997; Olsson & Poom, 2005) and that the measured capacity varies for different visual attributes, such as colors, gabor patches, random polygons, and faces (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005; Olsson & Poom, 2005).

Although the change detection task has become the standard procedure for the assessment of VWM, several criticisms have been raised in regard to this task (Hollingworth, 2003; Landman, Spekrijse, & Lamme, 2003; Makovski, Sussman, & Jiang, 2008). Moreover, by inducing participants to remember information for the sake of producing a memory, the task takes a “static approach” toward working memory. This approach can be contrasted

with everyday vision tasks, where working memory is often used dynamically. For example, Hayhoe and colleagues (Ballard, Hayhoe, & Pelz, 1995; Droll, Hayhoe, Triesch, & Sullivan, 2005; Hayhoe & Ballard, 2005) found that during visually guided motor tasks—such as picking up a blue block and placing it at a designated location—participants usually do not fill up their VWM capacity. Instead, they prefer to keep a single piece of information in VWM at once and look back at a display again when more information is needed. Thus, it is important that we assess the characteristics of VWM during online perception, which may differ from those of VWM in an idealized change-detection task.

Recent research by Soto, Downing, Woodman, and colleagues has revealed important interactions between VWM and online perception (Downing, 2000; Downing & Dodds, 2004; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006; Woodman & Luck, 2004, 2007; Woodman, Vogel, & Luck, 2001). For example, VWM can influence visual search when the contents of VWM are both relevant and irrelevant to the search task. Holding the exact target template in VWM and searching for that object results in faster search speed, in comparison with holding a general description of the target in working memory (Vickery, King, & Jiang, 2005; Wolfe, Butcher, Lee, & Hyle, 2003). Even when the contents of VWM are irrelevant to the search task, they can still modulate search performance. For example, in Soto et al.’s (2005) study, participants were asked to hold one object in VWM while conducting visual search during the memory retention intervals. A tilted line served as

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the search target, and vertical lines were designated as distractors. Each line was enclosed by an outline of a shape irrelevant to the search task. Critically, the shape currently maintained in VWM could surround the search target (congruent trials) or a distractor line (incongruent trials), or it could be absent from the search array (neutral trials). Soto et al. (2005) found that search response time (RT) was slower for incongruent trials than for the neutral trials, which were in turn slower than congruent trials. The congruity effect indicates that the contents of VWM bias attentional allocation during search, even though the VWM contents are, strictly speaking, irrelevant to the search task. Similar results have been demonstrated in other studies by Downing as well as Olivers and colleagues (Downing, 2000; Olivers, Meijer, & Theeuwes, 2006). The bias of attention by VWM contents, however, is not entirely automatic. If an object in VWM was never the search target, then search was not biased (Woodman & Luck, 2007).

To date, the two approaches of VWM research have largely been carried out in parallel to each other. Change detection research evaluates VWM capacity in an ideal situation, where no interference is present during the retention interval. The visual search congruity effect is an indirect approach to studying VWM. This approach has focused on demonstrating an influence of VWM on online perception, but has not explored issues related to VWM capacity. The main goal of the present research is to establish a link between these two approaches. Specifically, we used the visual search congruity effects as an indirect assessment of VWM and examined effects of memory load and feature complexity on the congruity effect.

To validate the use of the congruity effect as a means of assessing VWM, we first varied the number of objects held in VWM and tested whether the congruity effect diminished with increasing memory load. During the retention interval, one of these objects could enclose either the search target (congruent trials) or a distractor (incongruent trials). The search target was a tilted line among vertical lines, and the surrounding shapes were irrelevant to the task. We measured the size of the congruity effect as a function of the number of memory objects. Given that the strength of VWM representation declines with increasing load, we expected the congruity effect to decline as the load increased.

The sensitivity of congruity effect to VWM load allows us to further test other properties of VWM. Specifically, we are interested in whether the congruity effect is modulated by the complexity of the objects held in VWM. This topic has been controversial in change-detection studies. Using change detection, Alvarez and Cavanagh (2004) found that performance declines with increasing object complexity. For example, change-detection accuracy is higher when the memory items are color patches rather than random polygons. These results support the idea that the capacity of VWM is inversely related to the complexity of a memorized visual attribute. However, discrepancy in change detection of different visual attributes may re-

flect differences at the change comparison stage, since color patches tend to be more distinctive from one another than are random polygons. Thus, it is easier to detect a color change than a polygon change (Awh, Barton, & Vogel, 2007; Jiang, Shim, & Makovski, in press). Whether there is any difference between VWM's representation for simple and complex objects prior to the presentation of a memory probe remains controversial. In this study, we evaluated whether the modulation of VWM on visual search depends on the complexity of objects held in VWM. The *complexity independent hypothesis* predicts that the congruity effect is comparable when simple and complex objects are held in VWM, since VWM representation of complex attributes may be as good as that of simple attributes (Awh et al., 2007; Jiang et al., in press). Conversely, VWM may have a smaller modulation on search RT when complex objects are held in VWM (*complexity dependent hypothesis*).

EXPERIMENT 1

Memory Load and Figure "Goodness"

The basic experimental paradigm used in the present study is illustrated in Figure 1. On each trial, participants were presented with a memory array of one to three objects to hold in VWM. During the retention interval, a search array of vertical and tilted lines was presented. Participants searched for the uniquely tilted line and reported whether it was tilted to the left or to the right. The lines were enclosed by shapes, one of which matched an object held in VWM. That object could encompass either the search target (i.e., the tilted line) or a distractor (i.e., a vertical line). After the search response, a VWM probe array was presented, and participants judged whether this array was the same as or different from the memory array.

In this procedure, VWM was assessed both directly and indirectly. First, it was assessed directly by the change-detection task, which flanked the search task in temporal sequence. This task was similar to previous change-detection tasks used to measure VWM, except that an active search task—rather than a blank display—filled the retention interval. Second, VWM was assessed indirectly by visual search. Any modulation of VWM contents on visual search should result in faster search RT when the target—rather than a distractor—is enclosed by a memory object. Of interest is whether the RT congruity effect is influenced by memory load and by object complexity.

A novel aspect of Experiment 1 was our definition of "complexity." Object complexity is a controversial concept. Most previous VWM studies have followed Alvarez and Cavanagh's (2004) approach and have defined complexity using "informational load" as reflected by the slope of search RT as a function of display set size (see also Eng et al., 2005). The steeper the slope, the heavier the informational load, and the more complex the attribute is. For example, visual search of polygon shapes results in a steeper search slope than does visual search of colors. The index of informational load by visual search

Figure 1. A schematic illustration of a trial sequence tested in Experiment 1. Participants were told to remember the initial memory array. During the memory retention interval, they searched for a tilted line among vertical lines and reported the tilt direction. Subsequently, an array of memory probe was presented; participants judged whether it was the same as or different from the memory array. One of the memory objects surrounded either the search target (i.e., the tilted line, as shown here) or a search distractor (i.e., a vertical line). The big white circle on the visual search display is shown for illustrative purposes only and was not actually presented.

slope, however, can be criticized. Visual search is significantly influenced not only by the complexity of each object, but also by the similarity between targets and distractors (Duncan & Humphreys, 1989). Thus, search slope reflects an object's intrinsic complexity as well as the similarity between search objects. The same object, such as a face, would be regarded as low in informational load when searched for among squares, but high in informational load when searched for among other faces. Confounding object complexity with interobject similarity is a significant drawback of this index (Awh et al., 2007; Jiang et al., in press). An alternative definition of complexity independent of interobject similarity is preferred.

We adopted Garner's rotation and reflection (R&R) transformation principle as an alternative definition of object complexity (Garner, 1962; Garner & Sutliff, 1974). This definition was used to capture the "goodness" of an object. Garner suggested that the goodness of an object is determined by its relation to a possible set of objects produced by the original object's reflections and rotations. A perceptually "good" object is one that has a small set of R&R transformations. For example, a circle is a good object, because it does not change shape after R&R. A symmetric object is higher in the goodness index than an asymmetric object, because reflection does not result in a new shape (Attneave, 1957). The goodness of an object is initially used to describe a perceptual property of the object, corresponding to its

subjective simplicity (Hochberg & McAlister, 1953). Objectively, the goodness of an object has been shown to influence the speed of pattern discrimination (Garner & Sutliff, 1974) and visual search (Rauschenberger & Yantis, 2006). Because Garner's definition of figure "goodness" makes no reference to other objects, it does not confound interitem similarity with object complexity. A figure is "good" independently of its similarity to other figures. Guided by Garner's R&R transformation principle, we created two sets of stimuli. The set that is higher in figure goodness is considered the simpler set (Figure 2, top); the set that is lower in figure goodness is the more complex set (Figure 2, bottom).

To establish correspondence between Garner's principle and informational load used in previous studies (Alvarez & Cavanagh, 2004; Eng et al., 2005), participants in Experiment 1 were initially tested in a standard visual search task to measure search slopes for the simple and complex sets. Here, participants were searching for a predefined target object among four, six, or eight distractors selected from the same stimuli set. Search slope for the simple, "good" objects (56 msec/item) was significantly shallower than the slope for the complex objects (86 msec/item) [$F(1,12) = 15.82, p < .01$].

In sum, the orthogonal manipulation of memory set size and figure "goodness" allowed us to assess—from both the direct change-detection measure and the indirect search congruity effect—whether VWM was sensitive to memory load and object complexity.

Figure 2. Two sets of stimuli used in Experiment 1. The top row (simple objects) were figures with high “goodness” index. The bottom row (complex objects) were figures with low “goodness” index.

Method

Participants. Participants in all experiments were volunteers from either Harvard University or the University of Minnesota. They were 18 to 35 years old and had normal color vision and normal or corrected-to-normal visual acuity. Thirteen participants (mean age 25.7 years) completed Experiment 1.

Equipment. Participants were tested individually in a normally lit interior room. They sat unrestrained at approximately 57 cm from a 19-in. monitor. The experiments were programmed with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), implemented in MATLAB.

Materials. Objects used in the VWM task included 16 Garner shapes that were determined a priori using Garner’s R&R transformation principle (Garner, 1962; Garner & Sutliff, 1974). The eight simple shapes could produce a smaller set of objects with R&R than could the eight complex shapes (Figure 2). The shapes were solid white and resided within $4^\circ \times 4^\circ$. Stimuli used in the visual search task were red vertical or tilted lines (0.32° in length) that were enclosed by solid white shapes taken from the 16 Garner shapes. The tilted line was tilted 27° either to the left or to the right.

Presentation sequence. Figure 1 shows a schematic illustration of a trial. Each trial began with a white fixation cross (0.4°) presented against a black background for 500 msec. The fixation cross was removed, leaving the black background for 500 msec. Then, the memory array of one to three Garner shapes was presented against a black background. The shapes were placed equidistantly on an imaginary circle. The center distance of each shape was 6.4° away from fixation. Shapes from the memory array were sampled in three different ways that were equally probable: They could all be simple shapes (all simple), complex shapes (all complex), or a mixture of simple and complex shapes (mixed condition). Because we were unable to fully counterbalance the simple and complex shapes in the mixed condition, and because predictions about the mixed condition were not straightforward, in the following presentation, we focus on the all-simple and all-complex conditions only.

The memory array was presented for 1,000 msec and then was erased. After a retention interval of 600 msec, the visual search display was presented. The display consisted of four red lines (one tilted and three vertical) that were enclosed by four solid white shapes. The search items were presented equidistantly on an imaginary circle; the center of each item was 3.2° away from fixation. The shapes that surrounded the search items were irrelevant to the search task. However, they were sampled from the same Garner shapes used on the memory array, with the following constraints. (1) If the initial memory array contained all simple objects (or all complex objects), then the shapes on the search display were also all simple (or all complex). (2) One of the search items was enclosed by one of the shapes on the memory array; this item could be the target (congruent trials; 50% of trials) or a distractor (incongruent trials; 50% of trials). (3) The other search items were enclosed by shapes from the Garner sets (of the same com-

plexity as the memory shapes) not presented on the initial memory array. The search display was presented until participants pressed the left or right arrow key to indicate the tilt direction of the target line.

The VWM probe array was presented 500 msec after the search display was erased. The probe array was either identical to the memory array (50% of trials) or different, in that one shape was replaced by an object from the same complexity category not shown in the memory or search array. Participants pressed “d” (different) or “s” (same) to report detection of a change.

Each participant completed six blocks of 72 trials, divided randomly and evenly into three memory loads (one, two, or three objects), three complexity sets (all simple, all complex, and mixed), two visual search responses (target tilted to the left or to the right), two search types (congruent or incongruent), and two change-detection response types (change present or absent).

Results

Trials in which the visual search performance was incorrect (2% of all trials) were excluded from further analyses.

Change detection accuracy. Figure 3 shows change detection accuracy as a function of memory set size and figure “goodness.” Accuracy declined with increasing memory load [$F(2,24) = 62.57, p < .01$]. Figure “goodness” did not significantly influence accuracy [$F(1,12) = 2.73, p > .10$]. The two factors did not significantly interact with each other ($F < 1$). The estimated memory capacity (based on Cowan’s K ; Cowan, 2001) was slightly—but not significantly—higher for simple objects (1.34 objects)

Figure 3. Results from Experiment 1’s change detection task. Error bars show standard errors of the mean.

Figure 4. Results from Experiment 1: Visual search response time (RT) under visual working memory (VWM) load. Simple or complex objects (defined by Garner's rotation and reflection transformation principle) were held in VWM during search. Top: Visual search RT averaged across congruent and incongruent trials. Bottom: The size of congruity effect as a function of memory load and figure goodness. The congruity effect was calculated by the difference between incongruent and congruent trials, normalized by the mean of incongruent and congruent trials. Error bars show standard errors of the mean.

than for complex objects (1.21). These capacity estimates were likely an underestimation that was due to the use of relatively small set sizes (i.e., Cowan's K cannot exceed the largest memory load). The capacity was also reduced by interference from the visual search task (Makovski, Shim, & Jiang, 2006).

Visual search RT under VWM load. Averaged across congruent and incongruent trials (Figure 4, top), search RT was significantly slower when the search elements were surrounded by complex rather than by simple objects [$F(1,12) = 25.59, p < .01$]. This difference most likely reflected visual properties of the search array, since it was more complex when objects lower in figure goodness were presented. The initial memory load affected RT significantly [$F(2,24) = 4.44, p < .05$]. As we will see later, this effect was driven primarily by the presence of an incongruent effect at lower VWM load. The interaction between VWM load and complexity was not significant ($F < 1$).

VWM modulation on search RT: The congruity effect. If the contents of VWM modulated subsequent

search, then we should expect search RT to be faster when the search target, rather than a search distractor, was surrounded by a shape held in VWM. Because search RT was generally slower when search items were surrounded by complex rather than by simple objects, we normalized the congruity effect by dividing the difference between incongruent and congruent trials by the average of these two types of trials:

$$\text{Normalized congruity} = \frac{(\text{incongruent RT} - \text{congruent RT})}{\left[\frac{(\text{incongruent RT} + \text{congruent RT})}{2} \right]} \quad (1)$$

Statistics were conducted on the normalized congruity effect. Figure 4 (bottom) shows the normalized congruity effect, and Table 1 shows mean congruent RT and incongruent RT. An ANOVA showed that the normalized congruity effect declined as the initial memory set size increased [$F(2,24) = 5.1, p < .05$]. The main effect of figure goodness was not significant [$F(1,12) = 1.47, p >$

Table 1
Mean Response Time (in Milliseconds) in the Congruent and Incongruent Trials of Visual Search for Experiments 1–3

	Set Size 1		Set Size 2		Set Size 3	
	Congruent	Incongruent	Congruent	Incongruent	Congruent	Incongruent
Experiment 1						
Simple	811	944	838	839	846	846
Complex	959	1,016	968	964	943	958
Experiment 2						
Simple	962	933	976	992	945	951
Complex	1,060	1,112	1,044	1,035	1,045	1,044
Experiment 3						
Colors	1,014	1,138	1,039	1,103	—	—
Shapes	1,081	1,159	1,077	1,087	—	—

.25]. However, effects of figure goodness were obscured by the lack of a congruity effect at higher set sizes, leading to a marginally significant interaction between load and figure goodness [$F(2,24) = 2.70, p < .09$]. When analyzed separately, the congruity effect was not significant for complex objects at any of the memory loads (all $ps > .30$). In contrast, holding a simple object in VWM resulted in a significant congruity effect, which then declined with increasing load [$F(2,24) = 9.92, p < .01$]. The congruity effect produced by holding a single simple object in VWM was significantly greater than that produced by holding a single complex object in VWM [$t(12) = 2.20, p < .05$].

Discussion

Experiment 1 focused on an indirect assessment of VWM via its modulation on visual search. It replicated previous findings that the contents of VWM could bias the attentional allocation in visual search (Downing, 2000; Olivers et al., 2006; Soto et al., 2005). Search was faster when the target—rather than a distractor—was enclosed by an object currently held in VWM, even though the contents of VWM were irrelevant to the search task. Experiment 1 also showed that the modulation of VWM on search depended on the initial VWM load. The modulation effect was most obvious when the VWM load was low. This finding may seem inconsistent with past findings, where dual-task interference between visual search and VWM is strongest when VWM load is high (Woodman & Luck, 2004). However, dual-task interference sets search and VWM in competition with each other, whereas the congruency effect reflects a modulation of search by VWM contents. Thus, these two types of interactions are separable.

The VWM load effect on search congruity fits with the idea that objects are less well retained at higher VWM load. However, the rapid diminution was unexpected on the basis of the conventionally accepted capacity of VWM. Although most VWM studies put the capacity of VWM at approximately three or four objects, Experiment 1 showed that the search congruity effect diminished much more rapidly. In our experiment, change detection accuracy for two memory objects was reasonably high. Yet, in the indirect measure, the congruity effect became difficult to detect with two memory objects. Thus, although VWM may be able to hold

three to four objects, its influence on online perception is most obvious when the load is low. We will discuss the two approaches of VWM further in the General Discussion.

EXPERIMENT 2 Perceptual Priming?

Could the modulation of search by the memory task seen in Experiment 1 reflect perceptual priming rather than VWM modulation? This is unlikely, as shown in a previous study in which the modulation effect was largely eliminated when the initial memory array was passively viewed rather than actively remembered (Soto et al., 2005). Nonetheless, one could argue that the load and complexity effects on search congruity might be due to perceptual differences rather than to VWM differences. To find out whether perceptual priming could account for the results from Experiment 1, we carried out Experiment 2, which was exactly the same as Experiment 1, except that participants were told to ignore the first memory display and to concentrate only on the visual search task.

Method

Participants. Sixteen new participants completed Experiment 2. Their mean age was 23.8 years.

Procedure and Design. The procedure and design were the same as those used in Experiment 1, except that participants were told to ignore the initial memory display. They concentrated on the visual search task on the second display. Each trial concluded after the visual search response was made. The subsequent memory probe display was omitted from the presentation sequence.

Results and Discussion

Incorrect search trials (2%) were excluded from further analyses. Figure 5 shows search RT and the congruity effect.

Visual search RT without VWM load. Similar to Experiment 1, search RT was slower when items were surrounded by complex objects rather than by simple objects (Figure 5, top) [$F(1,15) = 35.59, p < .01$]. Because this result was observed when participants had ignored the initial memory image, the difference between simple and complex conditions must have resulted from perceptual differences on the search display. The main effect

Figure 5. Results from Experiment 2: Visual search response time (RT) without visual working memory load. Simple or complex objects (defined by Garner's rotation and reflection transformation principle) were viewed passively before search. Top: Visual search RT averaged across congruent and incongruent trials. Bottom: The size of congruity effect as a function of memory load and figure goodness. The congruity effect was normalized by Equation 1. Error bars show standard errors of the mean.

of memory load was insignificant [$F(2,30) = 1.40, p > .25$], as was the interaction between complexity and load [$F(2,30) = 2.84, p > .07$].

VWM modulation on search RT: The congruity effect. Unlike in Experiment 1, the congruity effect was absent (Figure 5, bottom; see also Table 1 for RT in congruent and incongruent conditions), suggesting that holding items in VWM was critical for producing a congruity effect. In an ANOVA on memory load and complexity, neither the main effects nor the interaction was significant.

EXPERIMENT 3 Are Simple Objects Easier to Compare Than Complex Objects?

So far, we have shown that visual search is modulated by the contents of VWM, provided that the contents of VWM are simple. How do we account for the complexity effect? There are at least two possibilities. One possibility is that the memory strength may be stronger for simple than for complex objects. An alternative possibility is that it is easier to compare two simple objects than two complex

objects. After all, for VWM contents to modulate search, some calculation of similarity between VWM contents and search elements must be performed. If it takes longer to compare two complex objects than two simple objects, then the modulation of VWM on search will be weaker for more complex objects, even if memory strength is comparable for simple and complex objects. Experiment 3 directly tested the second possibility by measuring the amount of time it takes observers to make a same–different comparison for two objects shown simultaneously. The two objects were either both simple or both complex. If participants are equally fast at comparing simple and complex objects, then the complexity effects seen in Experiment 1 cannot be attributed to differences at the comparison stage.

Method

Participants. Twenty-two participants, including the two authors, completed Experiment 3. Their mean age was 22.0 years.

Procedure and Design. Each trial began with a white fixation cross (0.4°) presented against a black background for 500 msec. Half a second after the fixation cross was removed, two objects were presented equidistantly on an imaginary circle centered 3.2° away from fixation. Participants were asked to evaluate—as quickly and as ac-

Figure 6. Results from Experiment 3: Response time (RT) of comparing simple or complex shapes. Error bars show standard errors of the mean.

curately as possible—whether or not the two objects were identical. The display was presented until participants pressed the “s” (same) or “d” (different) key to indicate their response.

In a simple block, the two objects were sampled from the simple set used in Experiment 1. The complex block featured objects sampled from the complex set. Within each block, the items were the same on half of the trials, and they were different on the rest. Each participant completed two simple and two complex blocks of 20 trials in a counterbalanced order.

Results and Discussion

Accuracy was high for both the simple (96.2%) and complex (96.6%) trials. Incorrect trials and trials deviating by more than 3 standard deviations from the mean were excluded from the RT analysis. The speed to make the comparison (Figure 6) was equivalent between simple and complex objects [$F(1,21) = 1.9, p > .17$]. The lack of a difference cannot be attributed to a lack of statistical power; participants were significantly faster when the two objects were the same than when they were different, showing the well-known “fast–same” effect (Keren, O’Hara, & Skelton, 1977) [$F(1,21) = 9.2, p < .01$, with an observed power of 0.82].

Experiment 3 showed that the speed to compare two simultaneously presented objects was unaffected by the complexity of these objects. Therefore, it is highly unlikely that comparison differences could fully account for the greater modulation of holding simpler objects in VWM on search. Another reason to think that comparison difficulty

could be dissociated from VWM’s modulation on search came from a study by Soto and Humphreys (2007). Participants of this study held in working memory a verbal label, a visual object that was identical to one of the search items, or a visual object that shared only one feature with one of the search items. Although it was faster to report “same” when an object was identical to rather than different from a memory object (Vickery et al., 2005), the congruity effect was comparable among the three conditions. Thus, reduced modulation of VWM on search for complex objects cannot be fully accounted for by comparison differences.

EXPERIMENT 4

Congruity Effects for Colors and Shapes

Experiment 1 confirmed that the modulation of VWM on search was sensitive to memory load and object complexity. As memory load increased, the congruity effect weakened. The increase in “load” could originate either from increasing the number of objects or from decreasing figure “goodness.” One weakness of the previous experiments, however, was the fact that different types of stimuli were used for simple and complex attributes. The main goal of Experiment 4 was to use the same stimuli but to vary the complexity by requiring participants to selectively remember either the color or the shape of the objects. Previous studies have shown that colors carry lower informational load and that they can be considered a simpler attribute than shape (Alvarez & Cavanagh, 2004; Eng et al., 2005; Song & Jiang, 2006). We took advantage of the difference between color and shape to investigate effects of complexity on VWM in Experiment 4. The stimuli used for VWM were random polygons with different colors and shapes. We instructed participants to remember either color or shape, on separate blocks. The main goal was to investigate whether the results from Experiment 1 generalized to stimuli that differed in the relevant VWM attribute, but not in perceptual input.

A second goal of Experiment 4 was to test whether VWM contents could modulate visual search when that content was completely task irrelevant. A recent study showed that if an object held in VWM was never a search target, then participants did not automatically bias attention toward the memory object (Woodman & Luck, 2007). In Experiment 1, the probability that an object in VWM would enclose the search target (rather than a distractor)

Figure 7. Two sample polygon shapes (each in all eight colors) used in Experiment 4.

Figure 8. Change detection accuracy from Experiment 4. Error bars show standard errors of the mean.

was 50%, even though there were three distractors and one target. Thus, the VWM contents provided some information regarding the location of the target. If participants simply look for an object held in VWM on the search display, then they would find the target on 50% of trials, which is significantly above chance (25% for a search display of four lines). Although the target could be searched via the instructed criterion (i.e., the uniquely tilted line), participants may rely on target predictability and use their VWM to guide search. The predictability involved in the design of Experiment 1 did not invalidate the conclusions drawn so far, because our discussion was not restricted to involuntary VWM guidance. Nonetheless, we wished to investigate whether VWM modulation would continue to be sensitive to memory load and object complexity when target predictability was eliminated. Therefore, in Experiment 4, the likelihood that a memory item would enclose the target (i.e., congruent trials) was reduced to 25%. A memory object was equally likely to contain a search target or any of the three distractors.

Finally, we employed concurrent articulatory suppression to reduce the possibility that effects of memory load and object complexity originated from differences in verbal naming.

Method

Participants. Fifteen participants (mean age, 21 years) completed Experiment 4.

Materials. We used the eight complex shapes from Experiment 1's complex set, and we highlighted the outline of the shapes in eight different colors (red, yellow, green, azure, blue, purple, brown, or ecru). Figure 7 displays two sample shapes in eight colors. Black lines were used in the visual search task.

Design and Procedure. The design and procedure were similar to those of Experiment 1, except for the following changes. Color and shape VWM were tested in separate blocks to reduce task-switching costs. Participants completed six blocks of each task (color or shape) in a counterbalanced order. Each block included 32 trials, divided randomly and evenly into two memory set sizes, two search response types (left or right tilted), two memory response types (change present or absent), and two congruity types (congruent or incongruent). At the beginning of each block, participants were instructed to remember either the shape or the color of the polygons. Participants were told to ignore the irrelevant dimension. On each trial, participants were shown one or two colored polygons and were asked to encode the instructed attribute. Four black lines were then presented on the search display,

one of which was the tilted target line. Each line was enclosed by an outline-colored polygon; the inner region of the polygon was always white. To ensure that the congruity effect was driven solely by the relevant attribute, we resampled the irrelevant attribute. The polygon that enclosed the target (on congruent trials) or distractor (on incongruent trials) only matched with the relevant dimension of one of the memory items. Importantly, in each block, 25% of the trials were congruent trials, whereas the rest were incongruent trials. Consequently, a memory object coincided with the search target on only 25% of the trials. Finally, to minimize verbal naming, participants were required to rehearse a three-letter word (specified at the beginning of each block) as quickly as they could throughout the block. Other aspects of the experiment were the same as those of Experiment 1.

Results

Trials in which the visual search task was completed incorrectly (5%) were excluded from further analyses.

Change-detection accuracy. Change-detection accuracy (Figure 8) declined both when memory set size increased [$F(1,14) = 55.0, p < .001$] and when complexity of memory attribute increased [$F(1,14) = 18.98, p < .01$]. The interaction between memory set size and feature complexity (color or shape) was also significant [$F(1,14) = 5.14, p < .05$]; the advantage of color performance over shape performance became more dramatic as memory set size increased.

Visual search RT under VWM load. Search RT was not significantly affected by the initial memory attribute (Figure 9, top; see Table 1 for detailed results) ($F < 1$) or by memory load [$F(1,14) = 3.13, p = .10$]. The interaction between memory load and feature complexity was insignificant [$F(1,14) = 2.63, p > .10$].

VWM modulation on search RT: The congruity effect. The search RT congruity effect, shown in Figure 9 (bottom), was modulated by both memory load and memory complexity. The congruity effect diminished as VWM load increased [$F(1,14) = 5.20, p < .05$], and it was smaller for shape memory than for color memory [$F(1,14) = 5.40, p < .05$]. The interaction effect was insignificant ($F < 1$). Follow-up *t* tests showed that the congruity effect was significant when VWM retained one color [$t(14) = 4.4, p < .01$] or two colors [$t(14) = 3.7, p < .01$]. The effect was also significant when VWM retained one shape [$t(14) = 2.5, p < .05$] but insignificant when VWM held two shapes [$t(14) < 1$].

Discussion

Consistent with those of Experiment 1, the results from Experiment 4 showed that the modulation of VWM contents on subsequent search depends on VWM load and complexity. The feature (color or shape) participants held in VWM determined the degree of modulation for the subsequent visual search. Color, a simple visual feature, was associated with higher VWM capacity than was shape. Holding color in VWM also produced a larger congruity effect on subsequent search. These results were observed, even when the VWM contents randomly coincided with the search target. Furthermore, a congruity effect for color was observed, despite the fact that objects held in VWM did not repeat their shapes on the search display. The mismatch in the irrelevant dimension did not eliminate the

Figure 9. Results from Experiment 4: Visual search response time (RT) under VWM load. Colors or shapes were held in VWM during search. Top: Visual search RT averaged across congruent and incongruent trials. Bottom: The size of congruity effect as a function of memory load and figure goodness. The congruity effect was normalized by Equation 1. Error bars show standard errors of the mean.

congruity effect, suggesting that the modulation of VWM on search does not rely on template matching of an integrated object (Soto & Humphreys, 2007).

GENERAL DISCUSSION

The goal of the present study was to establish a link between two approaches to the study of VWM. In one approach, VWM was directly assessed by a change-detection task, which has been instrumental in revealing a capacity limit of VWM (Alvarez & Cavanagh, 2004; Jiang, Olson, & Chun, 2000; Luck & Vogel, 1997; Pashler, 1988; Phillips, 1974). This research has shown that performance declines when objects held in VWM increase in number and in complexity. Change-detection research has remained agnostic to VWM's modulation of online perception because of its use of unfilled memory delay. The other approach tested visual search during the retention interval of a VWM task (Downing, 2000; Downing & Dodds, 2004;

Olivers et al., 2006; Soto et al., 2005; Soto et al., 2006). This research has shown that the current contents of VWM can modulate visual search, even when the search target is defined by an independent criterion. However, the scope of the second line of research has been limited to finding the kind of working memory that can guide perception (Huang & Pashler, 2007; Soto & Humphreys, 2007) and to evaluating whether the guidance is automatic or voluntary (Olivers et al., 2006; Soto et al., 2006; Woodman & Luck, 2007). The present study is our first attempt to relate these two directions of research. We manipulated memory load held during visual search and measured the size of search congruity for different memory set size and object complexity. We obtained three main findings.

First, the modulation of VWM on visual search is not "all or none" but is graded on the basis of the quality of the initial VWM representation. The greater the number of objects held in VWM, the coarser the VWM representation of each object (Wilken & Ma, 2004). This, in turn,

reduces the modulation of VWM on subsequent search. The sensitivity of search congruity to VWM load also validates the use of the indirect approach to assess VWM. Using this approach, we then asked whether a similar effect was found when memory objects increased in complexity rather than in number. Experiment 1 manipulated complexity by using shapes that differed in their figure goodness (Garner, 1962; Garner & Sutfill, 1974). Experiment 4 manipulated complexity by using the same objects but different memory attributes (polygon shape vs. color). The results of both experiments showed that search congruity diminished with increasing VWM complexity.

Second, we demonstrated that the modulation of VWM on subsequent search results from holding information in VWM rather than from perceptual priming. When the initial memory display was ignored rather than actively remembered, no modulation on visual search was observed (Experiment 2). By definition, the modulation is a "top-down" process: It requires active maintenance of information in VWM. However, the modulation on search is not necessarily intentional, given that the contents of VWM are irrelevant to the search and still affect search performance. Indeed, the search congruity effect was observed, even when the VWM contents did not predict which object on the search display was the target (Experiment 4). The modulation is therefore neither fully automatic nor fully voluntary (Downing, 2000; Soto et al., 2005; Woodman & Luck, 2007). It may reflect our inability to completely prevent the cross talk of two currently activated tasks.

Finally, our study has also provided suggestive evidence that the indirect assessment of VWM is more sensitive to load variations at the lower spectrum than is change detection. The search congruity effect was strongest when there was a single, simple object (or simple attribute) held in VWM. The effect became difficult to detect when VWM maintained two or more simple objects, or when one complex object was maintained. The rapid diminution of search congruity can be contrasted with change detection performance, which remained high when VWM maintained complex shapes or two or more visual objects. We argue that increasing VWM load reduced the strength of memory representation for each item (Wilken & Ma, 2004). In turn, the strength may have been too weak to influence visual search, even when VWM load did not exceed capacity limit. Increasing VWM load may also have reduced the probability that VWM would be used during online perception. Indeed, during visually guided motor tasks—such as picking up a colored block and placing it at a designated location—participants usually acquire one relevant feature at a time, rather than storing all features of an object simultaneously (Ballard et al., 1995; Droll et al., 2005; Hayhoe & Ballard, 2005). These findings suggest that although it is possible to store a few objects in VWM under ideal conditions, the interaction between VWM and online perception might be most obvious when VWM is not fully loaded. By systematically manipulating memory load and complexity, our study provides direct evidence for this idea.

What is the locus of the complexity effect as revealed by search congruity? Are simple and complex attributes encoded differently, consolidated differently, or represented

differently in VWM? The duration of the initial memory display (1,000 msec) should have enabled adequate encoding of fewer than three objects. In addition, the blank interval of 500 msec after encoding should have enabled the satisfactory consolidation of one to three objects into VWM, given that objects could be consolidated at approximately 50 msec/item (Vogel, Woodman, & Luck, 2006). Thus, it is unlikely that differences at the encoding or consolidation stage could account for the complexity effect observed in the present study. Even if there were systematic differences at the earlier stages, they would eventually result in differences in the representation (or retention) in VWM.

A more difficult question is whether the complexity effect might reflect differences at a comparison stage rather than differences of memory representation. However, this possibility was not substantiated by the data. Experiment 3 showed that the speed to perceptually match two objects was unaffected by object complexity. Thus, differences at the comparison stage alone cannot fully account for the complexity effect (see also Soto & Humphreys, 2007).

Conclusion

In summary, our study has shown that the modulation of online perception by VWM is revealed primarily when VWM load is low. Holding the number of memory objects constant, simple objects appear to be represented more strongly than complex objects, leading to a weaker modulation of visual search. We suggest that search congruity effect is a valuable tool to indirectly assess VWM attributes.

AUTHOR NOTE

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