Prepared or not prepared: Top-down modulation on memory of features and feature bindings

Cheng-Ta Yang [a,*], Philip Tseng [b], Kuan-Yao Huang [c], Yei-Yu Yeh [c,**]

[a] Department of Psychology, National Cheng Kung University, No. 1, University Rd., Tainan 701, Taiwan
[b] Institute of Cognitive Neuroscience, National Central University, No. 300, Jhongda Rd., Jhongli City, Taoyuan County 32001, Taiwan
[c] Department of Psychology, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 106, Taiwan

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ABSTRACT

Orienting attention to the to-be-tested representations can enhance representations and protect them from interference. Previous studies have found that this effect on feature and bound representations was comparable despite their difference in stability. This may have occurred because participants were tested in a block design, which is susceptible to participants' effective top-down control on the cued representations based on the predictability of the design. In this study, we investigated how the foreknowledge of when and what to expect would affect visual representations in a change-detection task. Cue onset time was either early or late; changes included either features or feature bindings. When predictability was maximized via a block design (Experiments 1, 5, and 6), early cues equally facilitated both representations while late cues did not affect either representation. When either cue onset time (Experiment 2) or change type (Experiment 3) was unpredictable, early cues consistently facilitated feature representations, while bound representations were enhanced only when cue onset time was predictable. Additionally, late cuing only cost bound representations. Finally, when both factors were no longer predictable via an intermixed design (Experiment 4), early-cuing benefit was eliminated, with a late cuing cost for the bound representations. These results highlight the critical role of effective top-down control in memory maintenance for visual representations.

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1. Introduction

Working memory plays a critical role in human's ability to temporarily store and manipulate information. This mechanism allows observers to integrate perceptual information with stored representations from long-term memory for complex cognitive tasks such as reasoning, learning, and comprehension. According to Baddeley's influential model of working memory (Baddeley, 1992, 2000; Baddeley & Hitch, 1974), there are a number of separate components in working memory, including the central executive and three independent subsystems. The three subsystems are involved in maintaining visuospatial (visuo-spatial sketchpad), verbal (phonological loop), and feature binding information (episodic buffer). The central executive is involved in asserting top-down control on binding information for achieving goal-directed behavior (Baddeley, 2012). This theoretical framework has been well-supported by numerous behavioral and neuroimaging data (see Baddeley, 2003, 2012 for reviews).

While researchers in the field of working memory focus on the existence and the functions of the subsystems, empirical research in the field of visual cognition has begun to uncover the nature of visual working memory. For one, visual working memory appears to be unstable and highly vulnerable to interference from subsequent visual inputs and masking (Landman, Spekreijse, & Lamme, 2003; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Sligte, Scholte, & Lamme, 2008; Sligte, Vandenbroucke, Scholte, & Lamme, 2010). Memory of a color square in an array is worse when another foil is presented with the test probe for a two-alternative-forced-choice judgment than when a single test probe is shown for a same–different judgment (Makovski, Watson, Koutstaal, & Jiang, 2010). Processing two test probes produces greater interference on visual working memory representations than a single test probe.

The degree of which visual working memory is subject to interference from subsequent stimuli appears to depend on what is being tested: features or feature bindings. Although visual working memory stores and maintains integrated object representations (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), bound representations have been shown to be more fragile than feature representations (Allen, Baddeley, & Hitch, 2006; Treisman & Zhang, 2006). In a change detection task, Treisman and Zhang (2006) demonstrated that memory of feature bindings is worse when the location of the test probe differs from that of the item in the memory array. In contrast, feature memory

* Correspondence to: Cheng-Ta Yang, Department of Psychology, National Cheng Kung University, No. 1, University Rd., Tainan 701, Taiwan. Tel.: +886 916 111 397; fax: +886 6 238 6728.
** Correspondence to: Yei-Yu Yeh, Department of Psychology, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 106, Taiwan. Tel.: +886 2 3366 3095; fax: +886 2 2366 1095.
E-mail addresses: yangct@mail.ncku.edu.tw (C.-T. Yang), yyy@ntu.edu.tw (Y.-Y. Yeh).

is not affected by the change in location. Allen et al. (2006) found that memory judgment that relied on binding information is worse when the to-be-memorized items are presented in sequence than when they are presented simultaneously. But such difference is not apparent in memory of features. In the same vein, Fougnie and Marois (2009) showed that judgment based on feature bindings is impaired to a greater extent than judgment based on features when participants must engage in a highly demanding visuospatial tracking task during retention interval that required constant shift of attention. Brown and Brockmole (2010) also demonstrated that memory of feature bindings was worse when a concurrent task was performed from encoding to test. These findings converge to suggest that bound representations are more volatile than feature representations.

A small number of studies have investigated how top-down control modulates feature and bound representations that have differential stability. Among these studies, two studies have found that effects of top-down control on memory of features were no larger than on memory of feature bindings (Delvenne, Cleeremans, & Laloyaux, 2010; Yeh, Yang, & Chiu, 2005). Following Wheeler and Treisman's (2002) influential work, Yeh et al. (2005) manipulated change type so that detection was based on either feature or bound representations. In addition, they presented a retro-cue either early (200 ms after the memory offset, the cue-to-test time was 700 ms) or late (800 ms after the memory offset, the cue-to-test time was 100 ms) for the engagement of top-down control on visual working memory representations during a retention interval of 900 ms. Their results showed that onset time of retro-cues did not interact with change type. Early cuing equally facilitated feature and bound representations and protected them from subsequent interference. The comparable benefit on feature and bound representations was observed perhaps because the cue-to-test time (700 ms) was sufficient for the engagement of top-down control on visual representations. For late cuing, it was hypothesized that late cuing should cost visual working memory representations because a short cue-to-test interval (100 ms) was insufficient to focus and retrieve the cued representations prior to the presence of retroactive interference caused by the test stimuli. The operations based on cue and the operations based on the test array may overlap in time so that dual-task concurrent cost occurs. Moreover, the short cue-to-test interval may also result in perceptual lateral masking. Memory, especially for the feature bindings, should be degraded compared with the no-cue condition. Surprisingly, in that study late cuing did not cost feature or bound representations, regardless of their differential stability. It was perhaps because an effective top-down control could offset the cost from late cuing on visual representations. Recently, Delvenne et al. (2010) replicated Yeh et al.'s findings of retro-cuing benefit.

Cost on memory of features and memory of feature bindings was also found to be comparable when top-down control is engaged in another task during the retention interval (Allen et al., 2006; Johnson, Hollingworth, & Luck, 2008). In these two studies, backward digit counting (Allen et al., 2006) and visual search (Johnson et al., 2008) was used as secondary tasks during an interval of 900 ms and 3 s, respectively. Their results showed that detection of binding changes was impaired to the same degree as detection of feature changes. Baddeley, Allen, and Hitch (2011) also found that maintenance of bound representations does not require additional attentional support than maintaining feature representations. Fougnie and Marois's (2009) study is the only study that found differential impairment on feature and binding change detection using a dynamic tracking task during an interval of 6.8 seconds.

It is intriguing that top-down control has comparable impacts on feature and bound representations that have differential stability. A methodological feature may have caused these findings: a block design was used for the manipulations. The predictable nature of this design allows the participants to configure a highly specific task set, a configuration of cognitive processes necessary for performing a task (Sakai,

2008), before performing the task because they know when and what to expect. Indeed, studies in the field of visual oculomotor control have shown that different levels of predictability, manipulated via a block or intermixed design, can have a profound impact on participants' behavioral performances (Chiau et al., 2011; Juan et al., 2008). Thus, the comparable effects found in the previous studies may have arisen from the participants' foreknowledge of specific experimental context in each block. In light of this, we postulate that the comparable effects of top-down control on feature and bound representations perhaps are observed only when top-down control can effectively operate on visual representations based on the foreknowledge of the task set. Once this foreknowledge is removed, we should observe differential impacts of top-down modulation on feature and bound representations because these two types of memory representations differ in stability.

In six experiments, we tested this prediction by manipulating the predictability of either change type, cue onset time, or both, using the aforementioned task from Yeh et al.'s (2005) study. In Experiments 1–5, two arrays of color squares were presented to the participants for deciding whether there was any change between the two arrays. A change included changes in color (feature-change condition) or in the binding of color and location (binding-change condition). In Experiment 6, two arrays of colored shapes were used for change detection. A change included in shape (feature-change condition) or in the binding of color and shape (binding-change condition). Cue onset time was either early (200 ms after memory offset) or late (800 ms after memory offset) during a retention interval of 900 ms in Experiments 1–4 and was either early (800 ms after memory offset) or late (1400 ms after memory offset) during a retention interval of 1500 ms in Experiments 5 and 6. In the early-cue condition, the cue-to-test time (700 ms) is sufficient for top-down control for either type of representations. In the late-cue condition, the cue-to-test interval (100 ms) is brief so that dual-task concurrent cost and perceptual lateral masking may hamper memory when top-down control is ineffective.

In Experiments 1, 5, and 6, we replicated Yeh et al.'s experiment so that both variables were predictable. We manipulated the predictability of each variable one at a time in Experiments 2 and 3, and intermixed both variables in Experiment 4. We examined how the predictability of cue onset time and the predictability of change type modulate the retro-cuing effects on feature and bound representations. When both manipulations are predictable, participants can configure a highly specific task set for the time window to initiate top-down control and for the level of information to be tested. When either manipulation is predictable, participants can configure a partial task set based on the foreknowledge. Without any predictability, participants cannot prepare for setting effective top-down control on visual representations. We examined how the foreknowledge influences feature and bound representations.

2. Experiment 1

The aim of Experiment 1 was to replicate Yeh et al.'s (2005) findings of comparable effects of top-down control on memory of features and feature bindings, using a block design. Different combinations of cue onset times and change types were tested in separate blocks. This manipulation enabled the participants to configure a highly specific task set in each block. We expected to replicate previous findings of comparable effects of top-down control on memory of features and memory of feature bindings. Early cuing should facilitate visual working memory representations and late cuing should not cost visual working memory representations regardless of the representations to be tested.

2.1. Method

2.1.1. Participants

Twenty-four undergraduate students from the National Taiwan University volunteered to participate in this experiment. Each undergraduate

received a bonus course credit in an introductory psychology course for his or her participation. All were 18 to 22 years old with normal or corrected-to-normal vision. All participants signed a written informed consent prior to the experimental session.

2.1.2. Equipment

A PC with a 3.40-GHz Intel Pentium IV processor controlled stimulus displays and recorded responses. The experiment was run with E-Prime 1.1 (Schneider, Eschman, & Zuccolotto, 2002). The visual events were presented on a 17-inch color monitor with a vertical refresh rate of 75 Hz.

2.1.3. Design, stimuli, and procedure

The design, stimuli, and procedure were exactly the same as those used in Yeh et al.'s (2005) study. A 2 (change type: color/binding)×3 (cue onset time: no cue/early cue/late cue)×2 (judgment type: same/ different) factorial design was conducted to construct trials. The display elements were composed of six colored squares on a gray background. Each square subtended a visual angle of 0.73° (horizontal)×0.70° (vertical) at a viewing distance of 60 cm and was placed in one of eight possible locations equally spaced in an invisible grid that subtended 8.6° (horizontal)×8.3° (vertical) around the center of the
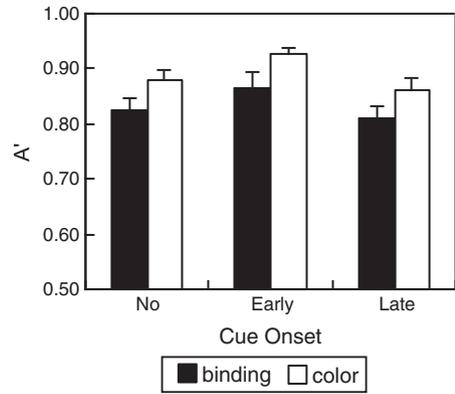

Fig. 2. Mean A' and standard error bar as a function of change type and cue onset time in Experiment 1.

screen. Each square was randomly chosen from a set of eight colors: red, green, orange, yellow, blue, cyan, magenta, and black.

Each trial consisted of two displays for the change detection task: a memory display and a test display. Changes occurred in the test display by either replacing two squares with two new colors that were not presented in the memory display (color-change condition), or by swapping two colored squares such that detection requires accurate memory of the combination of color and location (binding-change condition). See Fig. 1 for an example.

Cue onset time was manipulated to generate no-cue, early-cue, and late-cue conditions. In the no-cue condition, a blank interval was presented for 900 ms after the offset of the memory display. In the cue-present condition, two spatial cues in white were presented with a cue onset time at 200 ms (early cue) or 800 ms (late cue) after the memory offset, while the inter-stimulus interval (ISI) between the memory and test displays remained constant at a total of 900 ms across all conditions. The spatial cues pointed to the upper left corner of the two locations and were 100% valid, that is, changes would always appear at the cued locations.

The manipulations of change type (2 levels) and cue onset time (3 levels) together provided six combinations of experimental trials, which were tested separately in different blocks. The order of the blocks was counterbalanced across the participants. Each block began with six practice trials, followed by 32 formal trials. The test display was identical to the memory display in half of the trials, and contained changes in the other half.

Each trial began with a white fixation cross for 1500 ms (see Fig. 1). A memory display was then presented for 180 ms. The retention interval was 900 ms, and two spatial cues were presented according to the manipulation of cue onset time. The cues remained on the screen until the participants responded to the test display or 2 s had elapsed after the onset of the test display. The inter-trial interval was 2 s. Participants were told that when changes took place, the changes always appeared at the cued locations. Verbal suppression was used by instructing the participants to repeat "1-2-3-4-5-5-4-3-2-1" throughout the duration of each trial.

2.2. Results and discussion

Fig. 2 presents the results of mean A'[1] as a function of change type and cue onset time, and they were analyzed with a 2 (change type)×3 (cue onset time) repeated-measures analysis of variance (ANOVA). Mean percentage correct and false alarm rates observed
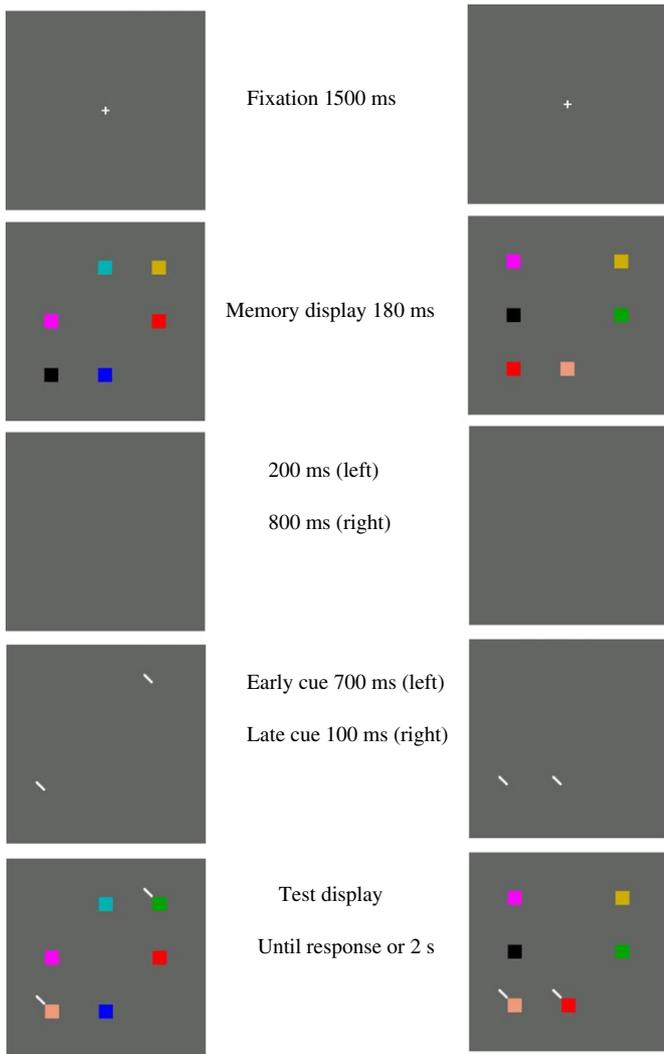

Fig. 1. An illustration of the experimental procedure used in Experiment 1. The left side is an example of the color change with early cues, while the right side is an example of the binding change with late cues.

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[1] A' is a nonparametric signal detection measure with a functional range of 0.5 (chance) to 1.0 (perfect sensitivity) (Grier, 1971). A' can correct for potential differences in response bias in the percentage correct data.

in all six experiments are reported in the Appendix A. Results showed that the main effect of change type was significant, [$F(1, 23) = 24.75$, $p < .005$, $\eta_p^2 = .52$], indicating that detecting a color change was more accurate than detecting a binding change with higher detection sensitivity. The main effect of cue onset time was also significant [$F(2, 46) = 13.57$, $p < .005$, $\eta_p^2 = .37$]. Tukey post hoc comparison revealed that detection sensitivity was higher in the early-cue condition than in the other two conditions. This benefit from early cuing suggested that participants effectively used the retro-cues to solidify the cued items into visual working memory for subsequent memory comparison and decision. Detection sensitivity in the late-cue condition was comparable to the sensitivity in the no-cue condition, suggesting that late cuing did not result in more interference on visual working memory representations even though the cue-to-test time was insufficient for strengthening memory representations. In addition, the interaction between change type and cue onset time was not statistically significant ($p > .3$). The null interaction effect suggested that the effects of top-down control were comparable across both change types.

These results replicated our previous findings (Yeh et al., 2005), showing that a color change was easily detected than a binding change with higher detection sensitivity. This finding is consistent with the suggestion that bound representations are more fragile than feature representations (Allen et al., 2006; Treisman & Zhang, 2006). Memory of feature bindings is easily interfered by the test stimuli. Despite differential stability, retro-cuing effects remained similar across both types of representations. These results suggested that when the participants can configure a highly specific task set for effective top-down control, they can use the early cues to solidify the cued items into working memory representations for subsequent memory comparison and decision. In addition, late cuing did not cause more interference than the no-cue condition, suggesting that an effective top-down control can offset the cost of late cuing on visual working memory representations.

3. Experiment 2

Results from Experiment 1 showed that comparable retro-cuing effects on both types of representations were observed with a block design. In this experiment, we dissociated the effect of cue onset time predictability from change type predictability by randomly intermixing different cue onset times within a block such that the participants *cannot* prepare for the time window of top-down control. Critically, change type was tested in separate blocks such that the participants *can* predict which type of memory representations would be tested. With this design of separate manipulation, we investigated whether the predictability of cue onset time is crucial for observing the comparable retro-cuing effects on feature and bound representations.

3.1. Method

3.1.1. Participants
Twenty-one undergraduate students from the National Cheng Kung University volunteered for this experiment. Each undergraduate received NT$ 50 for their participation. They were 18 to 28 years old and had normal or corrected-to-normal vision. All participants signed a written informed consent prior to the experimental session.

3.1.2. Design, stimuli, and procedure
The design, stimuli, and procedure were the same as in Experiment 1 except that cue onset time was randomly intermixed within each block.

3.2. Results and discussion

Fig. 3 presents the results of mean A' as a function of change type and cue onset time, and they were analyzed with a 2×3 repeated-
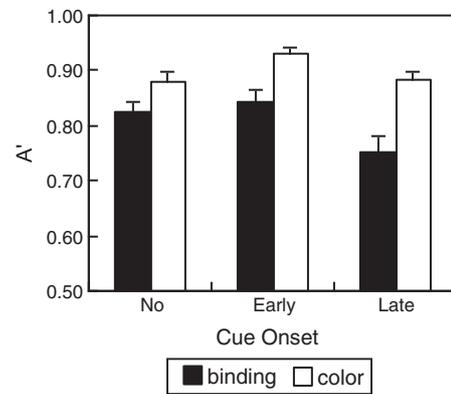

Fig. 3. Mean A' and standard error bar as a function of change type and cue onset time in Experiment 2.

measures ANOVA. Results revealed a significant main effect of change type [$F(1, 20) = 32.44$, $p < .001$, $\eta_p^2 = .62$], showing that detecting a color change was more accurate than detecting a binding change with higher detection sensitivity. The main effect of cue onset time was significant [$F(2, 40) = 22.04$, $p < .001$, $\eta_p^2 = .52$], showing that detection sensitivity was higher with early cues than no cue, which was in turn higher than the late cues. More important, the interaction between change type and cue onset time was also significant [$F(2, 40) = 4.43$, $p < .05$, $\eta_p^2 = .18$]. Tukey post hoc comparison revealed that detection sensitivity was lower when participants detected a binding change in the late-cue condition than in the other conditions; conversely, when detecting a color change with early cues, detection sensitivity was higher than late cues or no cue.

These results reveal that when the participants can make a prediction about the change type but not the cue onset time in advance, detecting a binding change would suffer from late cuing and detecting a color change would benefit from early cuing. This difference between the effect of early and late cues suggest that top-down control can have differential effects on feature and bound representations because of their differential stability. Given that the bound representations are more fragile than feature representations (Allen et al., 2006; Treisman & Zhang, 2006), memory of feature bindings is subject to subsequent interference to a greater degree than memory of features. Without knowing the cue onset time in advance, late cuing resulted in interference due to weak representations and insufficient time for retrieving the cued representation for further processing. As a result, the volatile bound representations received more retroactive interference from the subsequent test stimuli than feature representations. However, knowing that it is the memory of features that would be tested was sufficient to enhance the feature representations. When there was sufficient time for top-down modulation, top-down control was able to quickly configure a task set for strengthening the feature representations but not the fragile bound representations. The foreknowledge of cue onset time appears to be critical for observing comparable retro-cuing effects on feature and bound representations.

4. Experiment 3

In the third experiment, change type was manipulated within each block (unpredictable), and cue onset time was manipulated across blocks (predictable). Thus, the participants can predict the onset time of spatial cues and therefore effectively use the spatial cues to solidify the cued representations. But, they could not predict which change type would be tested. With this design, we investigated whether predictability of change type is crucial for observing the retro-cuing benefit on memory of features and memory of feature bindings.

4.1. Method

4.1.1. Participants

Twenty-four undergraduate students from the National Cheng Kung University volunteered for this experiment. Each undergraduate received NT$ 50 for their participation. All participants were 18 to 28 years old and had normal or corrected-to-normal vision. All participants signed a written informed consent prior to the experimental session.

4.1.2. Design, stimuli, and procedure

The design, stimuli, and procedure were the same as in Experiment 1 except that the change type was randomly intermixed within each block.

4.2. Results and discussion

Fig. 4 presents the results of mean A' as a function of change type and cue onset time, and they were analyzed with a 2×3 repeated-measures ANOVA. Results revealed a significant main effect of change type [$F(1, 23) = 54.68$, $p < .001$, $\eta_p^2 = .70$], showing that detecting a color change was more accurate than detecting a binding change with higher detection sensitivity. The main effect of cue onset time was significant [$F(2, 46) = 31.18$, $p < .001$, $\eta_p^2 = .58$], showing that detection sensitivity was higher with early cues than no cue, which was in turn higher than late cues. The two-way interaction was also significant [$F(2, 46) = 4.40$, $p < .05$, $\eta_p^2 = .16$]. Tukey post hoc comparison revealed that when a binding change was detected, detection sensitivity was higher in the early-cue condition than the no-cue condition, which in turn was higher than that in the late-cue condition. When a color change was detected, detection sensitivity was higher in the early-cue condition than in the no-cue and late-cue conditions.

These results reveal that when cue onset time was predictable and change type was unpredictable, early cuing facilitated both feature and bound representations while late cuing only cost bound representations. Knowing when early cues would occur was critical for observing comparable early-cuing benefits on feature and bound representations. However, knowing when late cues would occur did not offset the cost of retroactive interference on the more fragile bound representation. Although visual working memory of features such as colors (Makovski & Jiang, 2007; Makovski et al., 2010), orientations (Sligte et al., 2008), and shapes (Makovski et al., 2008) is fragile, memory of features was subject to less interference compared with memory of feature bindings when participants were prepared for memory judgment that occurred shortly after the late cues, which again highlights how top-down control modulates feature and bound representations to different degrees due to their differential stability.
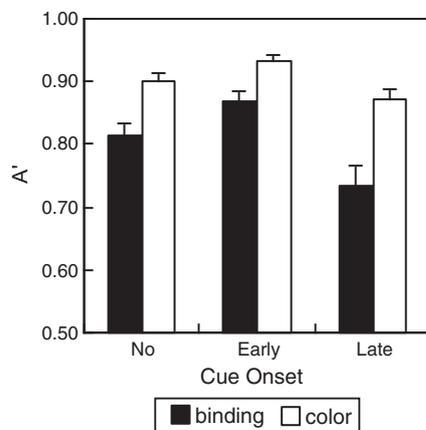
5. Experiment 4

In this experiment, we aimed to completely remove the possibility of effective top-down control on visual representations. To this end, change types and cue onset times were all randomly intermixed. We examined whether the participants can still use the spatial cues to strengthen the cued items to a coherent representation for memory comparison and detection when they cannot make a prediction about the experimental condition in advance.

5.1. Method

5.1.1. Participants

Twenty-one undergraduate students from the National Taiwan University volunteered for the experiment. Each undergraduate received credit in an introductory psychology course for their participation. All were 17 to 23 years old and had normal or corrected-to-normal vision. All participants signed a written informed consent prior to the experimental session.

5.1.2. Design, stimuli, and procedure

The design, stimuli, and procedure were the same as in Experiment 1 except that both the change type and cue onset time were randomly intermixed within each block. In such a case, participants cannot make a prediction about the forthcoming experimental condition in advance.

5.2. Results and discussion

Fig. 5 presents the results of mean A' as a function of change type and cue onset time, and they were analyzed with a 2×3 repeated-measures ANOVA. Results revealed a significant main effect of change type [$F(1, 20) = 87.91$, $p < .001$, $\eta_p^2 = .82$], showing that detecting a color change was more accurate than detecting a binding change with higher detection sensitivity. The main effect of cue onset time was not significant ($p > .05$). More importantly, the interaction between change type and cue onset time reached significance [$F(2, 40) = 9.10$, $p < .001$, $\eta_p^2 = .31$]. Tukey post hoc comparison revealed that detection sensitivity was lower when the participants detected a binding change with late cues than early cues or no cue; conversely, there were no differences in detection sensitivity across different cue onset times when a color change was detected. That is, memory of feature bindings was impaired in the late-cue condition and early cuing did not benefit either memory of features or memory of feature bindings.

These results suggest that top-down control cannot effectively modulate memory representations when participants cannot configure a task set based on the foreknowledge of when to engage top-down
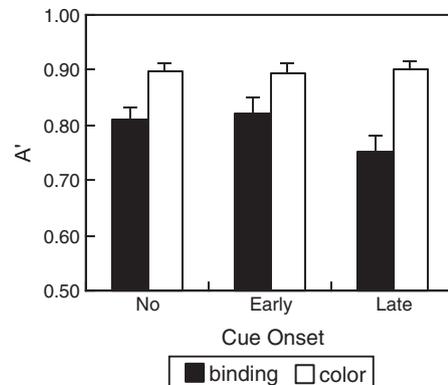
Fig. 4. Mean A' and standard error bar as a function of change type and cue onset time in Experiment 3.

Fig. 5. Mean A' and standard error bar as a function of change type and cue onset time in Experiment 4.

control and which type of memory representations would be tested. For feature memory, a partial task set for top-down control based on change type (Experiment 2) or cue onset time (Experiment 3) appears to be important for the enhancement of visual representations when early cues provided sufficient time (700 ms) for the engagement of top-down control. For memory of feature bindings, the foreknowledge of cue onset time (Experiments 1 and 3) is necessary for enhancing visual representations in the early-cue condition. The foreknowledge of both cue onset time and change type is necessary for offsetting the cost of late cuing.

6. Experiment 5

In Experiments 1–4, the retention interval was 900 ms, and the cue onset time was either 200 ms (early-cue) or 800 ms (late-cue) after memory offset. It is likely that the cuing effects simply reflected top-down control on two distinct memory systems between iconic memory and visual working memory in the early-cue and late-cue conditions, respectively. A delay of 800 ms in the late-cue condition may have already reduced enhancing effect from retro-cuing because of fast decay of iconic memory.

To investigate this possibility, this experiment modified Experiment 1 where all conditions were presented in separate blocks by adding an interval of 600 ms in the cue onset time. Thus, the retention interval was 1500 ms and the cue onset time was 800 ms in the early-cue condition and 1400 ms in the late-cue condition. Thus, both early and late cues operated on visual working memory because they were well beyond the range of iconic memory. If the findings of Experiment 1 were results of operating on two distinct memory systems, we should observe a different pattern of results here. Alternatively, if retro-cuing effects from Experiment 1 indeed resulted from effective top-down control on memory representations, we should observe a similar pattern of results because the cue-to-test interval was kept the same as in Experiment 1 (700 ms in the early-cue condition and 100 ms in the late-cue condition).

6.1. Methods

6.1.1. Participants

Nineteen undergraduate students from the National Cheng Kung University volunteered to participate in the experiment to receive monetary reward (NT$ 120). All were 19 to 24 years old and had normal or corrected-to-normal vision. All participants signed a written informed consent prior to the experimental session.

6.1.2. Design, stimuli, and procedure

The design, stimuli, and procedure were the same as in Experiment 1, except for two modifications. First, the retention interval was increased from 900 ms to 1500 ms. Second, the cue onset time was delayed compared to Experiment 1. In the early-cue condition, the cue onset time was 800 ms; in the late-cue condition, the cue onset time was 1400 ms.

6.2. Results and discussion

Fig. 6 presents the results of mean A' as a function of change type and cue onset time, and they were analyzed with a 2×3 repeated-measures ANOVA. Results showed a significant main effect of change type, [$F(1, 18) = 25.42$, $p < .005$, $\eta_p^2 = .59$], indicating that detecting a color change was more accurate than detecting a binding change with higher detection sensitivity. The main effect of cue onset time was also significant [$F(2, 36) = 5.15$, $p < .01$, $\eta_p^2 = .22$]. Tukey post hoc comparison revealed that detection sensitivity was higher in the early-cue condition than in the other two conditions. In addition, the interaction between change type and cue onset time was not statistically significant ($p > .3$). The
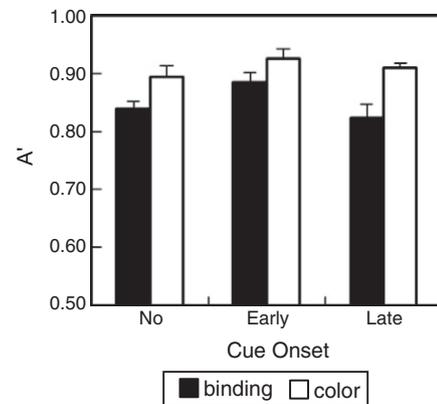

Fig. 6. Mean A' and standard error bar as a function of change type and cue onset time in Experiment 5.

non-significant interaction effect suggested that the effects of top-down control were comparable across both change types.

These findings showed a similar pattern of results to that in Experiment 1. When both early and late cues operate on visual working memory, early cues equally enhanced memory of features and feature bindings, and late cues did not cause more interference compared to the no-cue condition. Replication of the findings rules out the possibility that the cuing effects in Experiments 1–4 were results of operating on two distinct memory systems. Foreknowledge of cue onset time and change type allowed participants to configure a specific task set for effective top-down control over visual working memory representations. When there is sufficient time to solidify visual representations in the early-cue condition (700 ms in both Experiment 1 and this experiment), retro-cuing benefit occurs. When there is insufficient time to enhance memory representations in the late-cue condition (100 ms in both Experiment 1 and this experiment), neither benefit nor cost is observed.

7. Experiment 6

Results from Experiments 1–5 showed that foreknowledge of cue onset time and change type produced comparable retro-cuing effects on feature and bound representations. However, one would argue that the retro-cuing effects may have occurred because of the spatial nature of retro-cues (the cues indicated two locations) and the tested representations (color and location). In the color-change condition, the location of color must be encoded in order to make use of the spatial cues. In the binding-change condition, participants had to maintain the color-location bindings for accurate change detection. Therefore, in both color-change and binding-change conditions, the associations between color and location must be encoded and maintained in memory. The comparable retro-cuing effects on feature and bound representations may have occurred because both detecting feature-changes and binding-changes require memory of the color-location bindings.

To rule out this possibility, we tested memory of color-shape bindings in Experiment 6. Memory of color-shape bindings does not require the participants to memorize the association between features and locations. If comparable retro-cuing effects occurred because of the spatial nature of retro-cues that coincided with the spatial nature of the color-location memory, we should observe different effects of top-down control on memory of shapes and memory of color-shape bindings. Otherwise, we should find a similar pattern of results to that in Experiment 1.

7.1. Methods

7.1.1. Participants

Twenty undergraduate students from the National Cheng Kung University volunteered to participate in the experiment to receive

monetary reward (NT$ 120). All were 19 to 24 years old and had normal or corrected-to-normal vision. All participants signed a written informed consent prior to the experimental session.

7.1.2. Design, stimuli, and procedure

The design was similar to that of Experiment 1, but the manipulation of change type was modified. Shape memory was tested in the feature-change condition, and color-shape binding was tested in the biding-change condition. A set of 64 colored shapes were used, and the stimulus set was based on all possible combinations of eight shapes (see Fig. 7 for an example) and eight colors (same as in Experiment 1: red, green, orange, yellow, blue, cyan, magenta, and black). Each shape subtended a visual angle of approximately 1.06° × 1.06°. On each trial, four shapes were randomly selected from the stimulus set. Following Makovski et al.'s (2008) study, the four shapes were placed randomly at the four corners of a square grid that subtended an area of 6.96° × 6.96°. Colors and shapes were never repeated within any display at encoding or at test.

At test, four colored shapes were presented to test the memory of features (shape) or feature bindings (color-shape binding). In the shape-change condition, two shapes may change to new shapes and remain in the same color as in the memory display. In the binding-change condition, colors and shapes of two items in the memory display were re-combined in the test display. Locations of two colors changed in half of the trials and locations of two shapes changed in the other half. As a result, detecting a binding change required more information (color-shape binding) to be encoded and maintained than detecting a shape change. Only one spatial cue was used in the cue-present conditions. The retention interval and the manipulation of cue onset time were the same as the parameters in Experiment 5.

7.2. Results and discussion

Fig. 8 presents the results of mean A' as a function of change type and cue onset time, and they were analyzed with a 2×3 repeated-measures ANOVA. Results showed that the main effect of change type was marginally significant ($p = .07$). There was a trend showing that detecting a shape change was more accurate than detecting a binding change. The main effect of cue onset time was significant [$F(2, 38) = 8.39$, $p < .01$, $\eta_p^2 = .31$]. Tukey post hoc comparison revealed that detection sensitivity was higher in the early-cue condition than in the other two conditions. In addition, the interaction between change type and cue onset time was not statistically significant ($p > .5$). The non-significant interaction effect suggested that the effects of top-down control were comparable across both change types.

The current findings showed the same pattern of results as those in Experiments 1 and 5. When memory of shape and memory of color-shape bindings were tested, we still observed that early cuing equally enhanced the feature and bound representations. These results rule out the possibility that the comparable retro-cuing effect may have occurred due to the coincidental spatial nature between the retro-cues and the tested representations. In other words, the comparable retro-cuing benefit was observed because top-down control based on the foreknowledge of change type and cue onset time can effectively operate on visual representations.

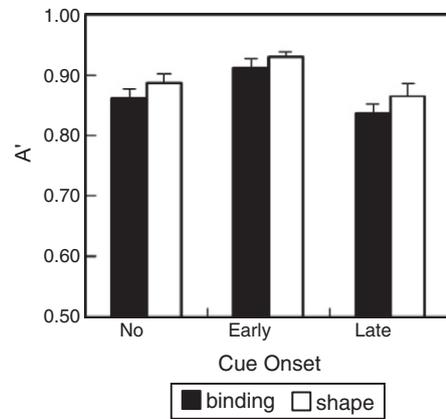**Fig. 7.** Eight possible colored shapes used in Experiment 6.

Fig. 8. Mean A' and standard error bar as a function of change type and cue onset time in Experiment 6.

8. General discussion

This study used a change detection task to examine the role of effective top-down control in strengthening and maintaining features and feature bindings in visual working memory for subsequent memory comparison and decision. Top-down control via orienting attention by retro-cues to the to-be-tested items has been proven to be an effective way to enhance feature representations and protect feature working memory (i.e., color, orientation, shape) from subsequence interference (i.e., new visual inputs, masking) (Griffin & Nobre, 2003; Makovski & Jiang, 2007; Makovski et al., 2008, 2010; Sligte et al., 2008). Top-down control enhanced target-specific neural activity in the early visual cortex when a cue was provided 200 ms or 1 s after the offset of an array of four gratings for an orientation judgment (Sergent, Ruff, Barbot, Driver, & Rees, 2010). Deployment of attention via retro-cuing at 200 ms stimulus offset can strengthen the functional connectivity between frontal and visual cortical regions (Kuo, Yeh, Chen, & D'Esposito, 2011).

With a block design, many previous studies have observed comparable benefit and cost of engaging and disengaging top-down control on strengthening and maintaining features and feature bindings into visual working memory representations (Allen et al., 2006; Baddeley et al., 2011; Delvenne et al., 2010; Johnson et al., 2008; Yeh et al., 2005; but see Fougnie & Marois, 2009 for an exception). This finding is intriguing because bound representations have usually been found to be more volatile than feature representations (Allen et al., 2006; Treisman & Zhang, 2006) and retrieval cues facilitated feature memory only (Saiki & Miyatsuji, 2009). Given the differential stability, one would assume that the more volatile bound representations would need greater control to enhance or protect the representations than control over feature memory. We postulate that the use of a block design in these studies may have allowed participants to configure a highly specific task set based on the foreknowledge of when to engage control and which type of memory representations would be tested. When such foreknowledge is removed, the differential stability should be manifested in the effects of top-down control on feature and bound representations.

We tested this hypothesis in the current study. Change type was manipulated to be on color or color-location binding (Experiments 1–5), or shape or color-shape binding (Experiment 6) that have differential stability. For the top-down control to operate on visual working memory representations, cue onset time was manipulated to be early (200 ms after memory offset, the cue-to-test time was 700 ms) or late (800 ms after memory offset, the cue-to-test time was 100 ms) during a retention interval of 900 ms in Experiments 1–4. The cue onset time was manipulated to be early (800 ms after memory offset, the cue-to-test time was 700 ms) or late (1400 ms after memory offset, the cue-to-test time

was 100 ms) during a retention interval of 1500 ms in Experiments 5–6. It has been shown that top-down control can bias attention via retro-cuing to visual representations of features (Astle, Summerfield, Griffin, & Nobre, 2011) and protect feature memory from subsequent interference (Makovski et al., 2010). The foreknowledge of cue onset time allows the participants to pre-set a critical time window for top-down modulation on visual representations effectively.

The results support that the differential stability between feature and bound representations has a significant impact on the operation of top-down control over visual working memory representations. Under early cuing, predictability of cue onset time was necessary for enhancing bound representations (Experiments 1, 3, 5, and 6) whereas the predictability of either cue onset time or the predictability of change type was sufficient to enhance feature representations (Experiments 2 and 3). Neither the predictability of cue onset time nor the predictability of change type affected feature representations in the late-cue condition compared to the no-cue condition (Experiments 2, 3, and 4). In contrast, the predictability of both cue onset time and change type was necessary to offset the cost of late cuing on bound representations (Experiments 1, 5, and 6). Without the foreknowledge of either manipulation, cost on bound representations was observed in the late-cue condition (Experiments 2, 3, and 4).

Together, these results show that effective top-down control is necessary to enhancing the cued representations, especially for the fragile bound representations. Effective top-down control relies on two factors: 1) the foreknowledge of when spatial attention should be engaged, and 2) sufficient time for top-down control to prioritize and strengthen the cued representations after the cue onset. In this context, early cuing produces comparable benefits for feature and bound representations. Without the foreknowledge of cue onset time, knowing which level of information would be tested is sufficient for top-down control to enhance feature representations when there is sufficient time to strengthen the cued representation of features.

In contrast to the findings in the early-cue condition, we found that the foreknowledge of when to engage control and the foreknowledge of which level of information are necessary for offsetting the cost of the late cuing on bound representations. Without either foreknowledge, memory of feature bindings is easily interfered. Compared to the no-cue condition, the interference may have resulted from the use of a short cue-to-test interval. The short interval may cause perceptual lateral masking and dual-task concurrent cost because of the operations based on the cue (orienting attention to the cue and retrieving the cued representation) are overlapping in time with the operations based on the test display (perceptual analysis of each item). Although we assumed that late cuing cost is a general mechanism that applies to both feature and bound representations, the current results may not support this assumption. Feature representations were not affected under late cuing even when both cue onset time and change type were unpredictable (Experiment 4). This nonsignificant cost on feature representations may have arisen because categorical colors that are highly discriminable (Olsson, Poom, & Treisman, 2005) and that the whole display at test provided retrieval context (Jiang, Olson, & Chun, 2000). Late cuing cost appears to be specific to bound representations in the current experimental context. Future research is needed to investigate whether late cuing cost is a general mechanism or specific to bound representations.

Comparing the results of Experiments 1, 5, and 6, we found that effective top-down control can enhance both iconic memory and visual working memory. The use of 200 ms as the cue onset time in the early-cue condition of Experiment 1 led to the doubt that the observed top-down control was enhancing iconic memory rather than visual working memory. The results of Experiments 5 and 6 ruled out this possibility by showing that effective top-down control could indeed enhance visual working memory as long as there was sufficient time for control to execute the operations based on the pre-defined task set. Late cuing cost on bound representations from Experiments 2, 3, and 4 was a

result of short cue-to-test interval rather than the decay of iconic memory. The replication of results of Experiment 1 in Experiment 6 also showed that effective top-down control benefitted memory representations regardless of the nature of the visual representations. Having configured a highly specific task set based on the foreknowledge, effective top-down control can enhance color, color-location, shape, and color-shape representations.

9. Conclusion

In conclusion, the results of the current study suggest a critical role of foreknowledge for effective top-down control to strengthen and maintain visual representations. Knowing when to initiate top-down control allows the strengthening of the cued items in memory representations for both feature and binding information. Without knowing when to initiate top-down control or which level of information would be tested, the differential stability of visual working memory representations is revealed in the late-cuing interference effect, where bound representations always suffer more than the feature representations. Future studies should take task set into consideration when trying to assess the impact of attention on feature binding and visual working memory.

Appendix A

Mean percentage correct data for Experiments 1–6.

	Same			Different		
	No cue	Early cue	Late cue	No cue	Early cue	Late cue
Experiment 1						
Binding	.86	.86	.82	.64	.78	.65
Color	.85	.84	.77	.81	.95	.84
Experiment 2						
Binding	.92	.82	.82	.55	.74	.53
Color	.91	.88	.88	.74	.92	.78
Experiment 3						
Binding	.92	.88	.78	.53	.74	.54
Color	.89	.88	.79	.82	.93	.85
Experiment 4						
Binding	.91	.79	.86	.53	.73	.53
Color	.92	.80	.78	.78	.90	.89
Experiment 5						
Binding	.86	.84	.85	.67	.84	.68
Color	.89	.87	.87	.81	.94	.87
Experiment 6						
Binding	.89	.87	.87	.70	.87	.65
Shape	.85	.89	.87	.82	.90	.76

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