Robust object-based encoding in visual working memory

Mowei Shen  
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, P.R. China

Ning Tang  
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, P.R. China

Fan Wu  
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, P.R. China

Rende Shui  
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, P.R. China

Zaifeng Gao  
Department of Psychology and Behavioral Sciences, Zhejiang University, Hang Zhou, P.R. China

Recently, researchers have begun to investigate how nonspatial perceptual information is extracted into visual working memory (VWM), focusing particularly on object-based encoding (OBE). That is, whenever even one feature-dimension is selected for entry into VWM, the others are also extracted automatically. While there is evidence supporting robust OBE in VWM, some researchers have argued that it is restricted to certain conditions, suggesting that OBE might be weak. The current study analyzed the experimental differences between prior studies revealing OBE and the ones that failed, and suggested that there were three critical differences in the experimental settings. Studies supporting robust OBE predominantly were conducted by probing an “irrelevant-change distracting effect,” in which a change of stored irrelevant-feature dramatically affects performance. To examine whether OBE in VWM is robust or weak, we manipulated these three aspects under the irrelevant-change distracting effect to check whether OBE could be erased. In three experiments, we found similar degrees of the distracting effect between the experimental condition (controlling these factors) and the control condition; this suggests that these factors do not affect OBE. We conclude that robust OBE exists in VWM.

Introduction

Visual working memory (VWM) stores a very limited amount of visual information (e.g., Baddeley, 2010; Hollingworth, 2006; Jiang, Makovski, & Shim, 2009; Xu & Chun, 2006; Zhang & Luck, 2008); for example, statistical estimation suggests that it holds a maximum of about three to four simple objects (Baddeley, 2012; Cowan, 2001; Fukuda, Awh, & Vogel, 2010). However, VWM has incredible relationships with many important, high-level human activities (e.g., Cowan et al., 2005; Hollingworth, Richard, & Luck, 2008; Hyun & Luck, 2007; Issen & Knill, 2012; Woodman, Luck, & Schall, 2007), and VWM status even offers valuable information on clinical diagnosis (e.g., Della Sala, Parra, Fabi, Luzzi, & Abrahams, 2012; Lee et al., 2010; Leonard et al., 2012; McCabe, Smith, & Parks, 2007; Park, Puschel, Sauter, Rentsch, & Hell, 2003). Consequently, researchers from various fields are interested in VWM. Using behavioral, event-related potentials (ERP), magnetoencephalography, and functional magnetic resonance imaging (fMRI) methods, investigators have examined multiple aspects of VWM, such as capacity, representation resolution, and information filtering in children, young adults, old adults, and people with neurological disorders (e.g., Bays & Husain, 2008; Cowan, Morey, Aubuchon, Zwilling, & Gilchrist, 2010; Grimault et al., 2009; Jost, Bryck, Vogel, & Mayr, 2011; Lee et al., 2010; Lopez-Crespo, Daza, & Mendez-Lopez, 2012; van den Berg, Shin, Chou, George, & Ma, 2012; Xu & Chun, 2006).

Recently, researchers have begun to investigate another new aspect of information processing in VWM: How nonspatial perceptual information is extracted into VWM to form a stable representation (Gao, Gao,
Li, Sun, & Shen, 2011; Gao, Li, Yin, & Shen, 2010; Woodman & Vogel, 2008; Xu, 2010; Yin, Zhou et al., 2012; Zhou et al., 2011). Visual attention selects information for visual perception in an object-based manner, and most previous VWM literature has assumed that VWM stores multiple-featured objects in an object-based manner; therefore, the critical question explored in this line of research was whether object-based encoding (OBE) also takes place in VWM. As a matter of fact, Alvarez and Cavanagh (2004) had already proposed that this processing manner may exist in VWM, such that a set of core visual features (e.g., simple color, orientation) are retained in VWM regardless of the observer’s intention. To test this hypothesis, researchers predominantly used multiple-featured objects (e.g., colored shapes) as the stimuli of interest and required the participants to remember one feature-dimension while ignoring any others. Adopting this type of manipulation, previous studies demonstrated that irrelevant spatial information was encoded into VWM automatically (e.g., Jiang, Olson, & Chun, 2000; Treisman & Zhang, 2006), obeying the OBE manner. Surprisingly, when using nonspatial visual features as the task-irrelevant information, the initial findings ran contrary to the OBE hypothesis, favoring a feature-based selection manner in VWM (Serences, Ester, Vogel, & Awh, 2009; Woodman & Vogel, 2008). That is, the participants could perfectly restrict their selection to the task-relevant information while filtering out the irrelevant part. In contrast to this strong, feature-based encoding manner, a later fMRI study supported weak OBE in VWM: the irrelevant simple visual features could be selected into VWM, but only in a low-memory-load condition (e.g., remembering two objects); in a high-memory-load condition (e.g., remembering six objects), the irrelevant features were no longer processed (Xu, 2010). However, recent ERP and behavioral studies have consistently suggested that although the capacity of VWM is fairly limited, VWM always selects irrelevant, high-discriminable visual information regardless of memory load (Gao et al., 2010; Yin, Zhou et al., 2012; Zhou et al., 2011); this supports robust OBE. Indeed, this robust manner has also been revealed in various feature-dimensions (e.g., simple colors, shapes, orientations, sizes), and remains constant at least from 6 or 7 years to 72 years of age (Zhang, Shen, Tang, Zhao, & Gao, submitted). Moreover, irrelevant information can be maintained in VWM for a fairly long period: it can be detected even 4 s after the encoding of the memory array (Yin et al., 2011).

The establishment of the OBE processing fashion in VWM is important, particularly in that it can help to reveal the intimate interaction among visual perception, VWM, and visual attention (Gao et al., 2011; Gao et al., 2010). However, although robust OBE for irrelevant, high-discriminable information has received consistent support from behavioral and ERP studies (e.g., Gao et al., 2011; Gao et al., 2010; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Yin, Gao et al., 2012), evidence supporting robust OBE has come from different experimental settings (see Table 1 in Supplementary Material and the following description for details) relative to those supporting feature-based encoding or weak OBE. Although these different experimental settings might imply that the ones used in supporting robust OBE were more sensitive in revealing OBE, they may act as critical factors that modulate participants’ processing manner and hence lead to support for the weak OBE hypothesis. Therefore, it is important to examine the influences of these experimental differences, so that we can determine whether robust or weak OBE takes place in VWM. Three critical differences in the experimental settings are summarized in following text.

First, in almost all studies demonstrating OBE, the exposure time to the memory array was between 100 and 500 ms (but see Marshall & Bays, 2012). In contrast, in a critical study supporting feature-based selection, the memory array was displayed for 1000 ms (Serences et al., 2009). Recent studies implied that the exposure time to the memory array could play an important role in determining the fate of the distracting information. Sander, Werkle-Bergner, and Lindenberger (2011a, 2011b) suggested that two different factors contribute to the participants’ final performance: low-level feature binding and top-down control. The former was initiated rapidly with the onset of the memory array in order to integrate fleeting perceptual information into coherent representations stored in VWM, whereas top-down control—which is mediated by the prefrontal cortex—begins to interact with the already-stored representation later and acts over a longer duration than the former. Consequently, a short exposure time is sufficient for feature-binding but not for top-down control. Supporting this claim, Sander et al. (2011b) demonstrated that in a situation containing targets and distracters in distinct locations, the interference induced by the distracters was largest at 100-ms exposure time and dropped as the exposure time of the memory array increased; this pattern was observed in both children and young and old adults, and the interference completely vanished at 1000 ms in the young adults. Considering that the previously demonstrated OBE seems to reflect automatic binding and arises within relatively short exposure times (<500 ms), it is thus possible that OBE is a transitory phenomenon that only occurs at the early stages of information processing. Given sufficient processing time, top-down control may gain enough power to exclude (or fully suppress) the irrelevant feature from VWM, which may well explain why feature-based
Second, evidence supporting robust OBE comes from change-detection tasks exhibiting an “irrelevant-change distracting effect.” Particularly, in a change-detection task by manipulating the change of the irrelevant feature, researchers have consistently found that the irrelevant feature change in the test array dramatically influenced behavioral performance of the target feature (cf. Gao et al., 2010; Hyun et al., 2009; Yin, Zhou et al., 2012). To balance the change rate between the relevant and irrelevant features, the irrelevant feature was changed in 50% of the trials. However, in experiments revealing feature-based selection, researchers kept the irrelevant feature constant throughout each trial. It is possible that this experimental setting changed the participants’ processing strategy. Indeed, with a change rate of 50%, the irrelevant feature change is not a rare event; this may make the irrelevant feature hard to be ignored. Therefore, although the participants were explicitly told to ignore the irrelevant feature otherwise it would do harm to the task, they could not completely follow the instructions. Related experimental instructions used in previous studies observing robust OBE may also trigger the participants’ curiosity: they might wonder what was so significant about the irrelevant feature that the experimenter emphasized it, and therefore they might ultimately process it anyway.

Finally, it is also possible that the task load was relatively low in previous studies supporting robust OBE. Consequently, after the processing of task-relevant features was complete, there were still sufficient resources to process the irrelevant features. A recent study revealed that relevant and irrelevant features may share one mental resource pool, since processing task-irrelevant features has been shown to reduce the precision of relevant features stored in VWM (Marshall & Bays, 2012). Notably, in one study supporting feature-based encoding, the memory array was displayed for only 23 ms and was followed by pattern masks (Woodman & Vogel, 2008). This setting made the task load of the target feature-dimension rather high. In line with this explanation, Xu (2010) found that in a memory load condition exceeding the VWM capacity (six feature-values), OBE of irrelevant features vanished. Although we recently found a different pattern of results than Xu (Yin, Zhou et al., 2012), this alternative is still a possibility.

To this end, the current study examined whether OBE in VWM is robust or weak. We explored this question by manipulating the above three issues in three experiments adopting the “irrelevant-change distracting effect.” Experiment 1 addressed the first issue, and Experiments 2 and 3 addressed the other two issues. If we erase OBE under even one of these conditions, then the weak OBE hypothesis is supported. In contrast, if none of these critical factors affects OBE, then the robust OBE hypothesis is supported.

### Experiment 1

We first examined the influence of top-down control on OBE by setting the exposure time to two visual objects as 100 or 1000 ms. Since the capacity of VWM is three to four simple objects, and since participants can readily finish the task even under 100-ms exposure time (Luck & Vogel, 1997), an exposure time of 1000 ms is taken as sufficient for encoding and exerting top-down control. Using the same exposure time settings, Sander et al. (2011) demonstrated that young adults in the 1000-ms condition (but not the 100-ms condition) could exclude the influence of distracting information displayed in distinct locations. If top-down control indeed affected the OBE, then the distracting effect would be reduced or disappear in the 1000-ms condition.

### Method

#### Participants

Fourteen Zhejiang University undergraduates (eight men; age 18–25 years) volunteered to participate in the experiment and signed consent forms. All had normal color vision and normal or corrected-to-normal visual acuity.

#### Stimuli and apparatus

Colored shapes were used as stimuli (subtending 1.64° by 1.64° of visual angle from a viewing distance of 60 cm), and color was the target dimension. A set of seven distinct shapes and seven colors (see Figure 1) were used in the experiment. In each trial, two distinct colored shapes were presented in two of six spatial locations, which were evenly distributed (separated by angles of 60°) in an invisible circle with a radius of 2.86° around the center of screen. The stimuli were presented on a gray (128, 128, 128, RGB) background on a 17-inch CRT monitor.

![Figure 1. The seven shapes and colors used in Experiment 1.](https://i.imgur.com/320x112.png)
Procedure and analysis

Each trial began with a 200-ms cross fixation to warn the participant of the start of a trial (Figure 2). Then, a memory array was presented on the screen for either 100 ms or 1000 ms, followed by a 1000-ms blank interval. Finally, a test array was presented on the screen until a response was initiated. If no response was made within 2000 ms, a new trial started automatically. The memory and test arrays each contained two objects. The participants were explicitly instructed to detect whether a color changed between the memory and test arrays while ignoring the shape, which would impair their performance if they attended to it. The intertrial blank interval was 600 to 800 ms. Seating in a dark and sound-shielded room, the participants were instructed to press F on the keyboard if a color changed or J if not. Both response accuracy and reaction time (RT) were emphasized and recorded.

The color and the shape in the test array were changed independently, each with a probability of 50%. When a change occurred, a new feature not used in the memory array was adopted in the test array. Therefore, there were two types of relationship between the memory and test arrays in terms of the irrelevant feature: either the shapes were identical (No-change), or the shape of one object changed in the test array (Irrelevant-change). When both shape and color changed, the changes occurred on the same object. A 2 (Exposure-time: 100 ms vs. 1000 ms) by 2 (Change-type: No-change vs. Irrelevant-change) within-subjects design was used. There were 64 trials in each condition, resulting in 256 total trials per participant (ordered randomly). The experiment was divided into four blocks with 5-min breaks between blocks; the total duration of the experimental session was about 25 min. Before the formal experiments, 20 practice trials were completed to ensure that the participants understood the instructions.

Evidence from previous studies supporting robust OBE implies that no behavioral index consistently reveals OBE (see Yin, Zhou et al., 2012, for example, and also the Dependent variables column in Table 1 of Supplementary Material). In order to capture OBE, we took accuracy and RT as indices of interest. Moreover, Accuracy was determined in terms of signal detection theory, which allowed us to disentangle sensitivity (d’) to the change from response bias (criterion). Therefore, whether or not all three indices reveal OBE cannot shed light on the robustness of OBE. Even if all of them demonstrated OBE in the experimental session, if OBE was significantly reduced compared to the control session, then a weak OBE would be supported. Two-way repeated analyses of variance (ANOVAs) with Exposure-time and Change-type as within-subjects factors were conducted on d’, criterion, and RT.

Results and discussion

As shown in Figure 3, in both Exposure-time conditions, the irrelevant change influenced behavioral performance. The two-way ANOVA showed that for d’ and criterion, neither the main effect of Change-type nor the main effect of Exposure-time reached significance ($p > 0.05$). However, a significant main effect of Change-type was revealed for RT, $F(1, 12) = 19.08, p = 0.001, \eta^2_p = 0.61$, indicating that the response time was significantly delayed under the Irrelevant-change condition (761 ms) relative to the No-change condition (737 ms). This result suggests that OBE takes place. The main effect of Exposure-time was also significant for RT, $F(1, 12) = 15.96, p < 0.001, \eta^2_p = 0.57$, suggesting that RT was quicker in the 1000-ms (736 ms) than the 100-ms (762 ms) conditions. Importantly, the two-way ANOVA did not reveal any significant Exposure-time $\times$ Change-type interaction on d’, criterion, or RT ($F < 1$), implying that the distracting effect occurred equally in both Exposure-time conditions.

In contrast to the prediction that the distracting effect would be erased (or at least reduced) under 1000-ms exposure time relative to 100 ms, we did not find any significant interaction between Exposure-time and Change-type. Therefore, the same degree of distracting effect due to change in an irrelevant attribute was revealed in Experiment 1, suggesting that the OBE is not a fleeting phenomenon that is only detectable when the binding factor facilitates it. Instead, it is rather robust, as irrelevant information could not be erased from VWM or be suppressed by top-down control.

Experiment 2

Experiment 2 was designed to address the two remaining alternatives: (a) the relatively high change rate of the irrelevant change and information provided to the participants about change in the irrelevant feature affect participants’ processing strategies, and (b) the main task (i.e., processing of the relevant feature-dimension) did not exhaust the participants’...
resources, so they could spare additional resources for the irrelevant feature-dimension.

Accordingly, we conducted the following three manipulations to examine the above two alternatives: (a) we reduced the change rate of the Irrelevant-change from 50\% to 20\%, so that the Irrelevant-change would have a relatively low probability while maintaining the experiment duration within an acceptable range; (b) we did not inform the participants that the irrelevant feature could be changed; and (c) following our previous work (Yin, Zhou et al., 2012), we set the memory load as six objects. We also added a secondary verbal rehearsal task in order to consume as many mental resources as possible (Fougnie & Marois, 2011; Ricker, Cowan, & Morey, 2010).

Since Experiment 1 did not reveal any effects of the critical manipulation, we applied all three of the above manipulations in one critical experimental session to find a situation that having the largest probability to erase the OBE manner. In addition, to provide a direct comparison with the above manipulations, we also employed a control session, in which none of the above manipulations was exerted except for the six objects maintained by the participants.

**Method**

To avoid potential contamination of the experimental session due to the control manipulation, the experimental and control sessions were completed by two different groups of participants. Each group contained 14 undergraduates (three men in the experimental group and six men in the control group; age 18–25 years). The memory array contained six objects, which were evenly distributed in an invisible circle and displayed for 200 ms.

In the experimental session (dual tasks), the participants were required to focus on the task-relevant feature and were not informed that the irrelevant feature could change. A letter rehearsal task was added before the memory task. In this secondary task, each time two random letters were displayed at the center of the screen (see Figure 4), the participants were required to repeat the two letters loudly throughout the trial. Instead of adopting the previous studies’ change rate of 50\%, the irrelevant feature changed in only 20\% of Experiment 2’s trials. Each participant completed 320 trials in total, only 64 of which contained the Irrelevant-change (the color changed in 32 trials but did not change in 32 trials). The entire experimental session was divided into four blocks separated by 5-min breaks, lasting about 45 min in total. For the control session (single task), only the memory task was completed. Moreover, the participants were told that the irrelevant feature could change in 50\% of the trials; however, they had to ignore it, lest it harm their performance. There were 64 trials with each of Irrelevant-change and No-change, resulting in 128 total trials (which were ordered randomly). The control session was divided into two blocks separated by a 5-min break; thus, the entire control session lasted about 15 min.

Mixed ANOVAs with Change-type as a within-subjects factor and Condition (dual tasks vs. single task) as a between-subjects factor were conducted on d’, criterion, and RT. The other analyses were the same as in Experiment 1.

**Results and discussion**

Figure 5 shows the results of Experiment 2. For d’, the mixed ANOVA demonstrated that the main effects of Change-type and Condition were not significant (p > 0.05). For criterion, the main effect of Change-type was not significant (F < 1), but a significant main effect of Condition was revealed, F(1, 26) = 26.84, p < 0.01, ηp² = 0.51, suggesting that the participants showed a stronger tendency to press “change” under dual tasks (0.40) than under a single task (1.75). For RT, the main
effect of Condition was not significant \((F < 1)\). However, similar to Experiment 1, the mixed ANOVA revealed a significant main effect of Change-type on RT, \(F(1, 26) = 5.58, p = 0.026, \eta^2_p = 0.18\), suggesting that RT was considerably delayed under the Irrelevant-change (869 ms) compared with the No-change (843 ms) conditions. Finally, the Change-type by Condition interaction was not significant on \(d'\), \(F(1, 26) = 1.25, p = 0.27, \eta^2_p = 0.05\); criterion, \(F(1, 26) = 1.80, p = 0.19, \eta^2_p = 0.06\); or RT, \(F(1, 26) = 2.31, p = 0.14, \eta^2_p = 0.08\), implying that OBE occurred equally in both the dual-tasks and single-task conditions.

Although we controlled both alternatives in the experimental condition, each of which may reduce or erase the distracting effect, similar OBE as in the control condition was still revealed. Therefore, these results suggest that OBE is not affected by these factors, further supporting the robust OBE hypothesis.

**Experiment 3**

One may argue that the critical manipulations in Experiment 2 were still not strong enough to erase or reduce OBE. In Experiment 3, we tested a condition that was more rigorous than Experiment 2’s dual-task condition:

1. The memory load was increased to eight objects.
2. The load of the secondary rehearsal task was increased to three letters.
3. Since Experiment 1 suggested that the encoding time of the memory array did not affect OBE, we reduced the exposure time to the memory array to 100 ms. In this way, the mental load of processing the relevant information was further increased.
4. The change rate of the Irrelevant-change was dropped from 20% to 16%, making the Irrelevant-change a rare event and the duration of the experiment similar to that of Experiment 2’s dual-task session.

To examine whether the above manipulations affect OBE, we compared performance in Experiment 3 with that under Experiment 2’s dual-task session.

**Method**

Fourteen new undergraduates (six men; age 18–25 years) participated in Experiment 3. Three new simple shapes and colors were added to the materials used in
Experiments 1 and 2 (for examples of the new materials, see the three colored shapes on the bottom of memory array in Figure 6), so that the colored shapes could be used throughout each trial without repetition. The memory array contained eight objects, which were evenly distributed in an invisible circle and displayed for 100 ms. In the secondary rehearsal task, three random letters were displayed at the center of screen. The irrelevant feature changed in 16% of the trials. Each participant completed 400 trials, only 64 of which contained the Irrelevant-change (the color changed in 32 trials but did not change in 32 trials). The entire session was divided into four blocks separated by 5-min breaks, lasting about 55 min in total. Since the task was more difficult than the previous ones, the participants were given 50 practice trials to familiarize themselves with the procedure. To compare the distracting effect between Experiment 3 and the dual-task session of Experiment 2, mixed ANOVAs with Change-type as a within-subjects factor and Condition (Experiment 2 vs. Experiment 3) as a between-subjects factor were conducted on d’, criterion, and RT.1

The other aspects were identical to Experiment 2.

Results and discussion

The mean accuracy across the 14 participants was 64% (SD = 0.04). Figure 7 shows the results for Experiment 3 and the dual-task condition of Experiment 2. The mixed ANOVA for d’ revealed a significant main effect of Condition [F(1, 26) = 7.38, p = 0.01, \( \eta^2_p = .22 \)], indicating that d’ was considerably lower in Experiment 3 (0.77) than in Experiment 2 (1.18). This result suggests that relative to the dual-task condition of Experiment 2, the current mental load was indeed significantly increased. The main effect of Change-type on d’ was not significant (F < 1). For criterion, the main effect of Condition was not significant (F < 1), but the main effect of Change-type reached significance, F(1, 26) = 21.00, p < 0.01, \( \eta^2_p = 0.45 \), suggesting that participants had a stronger tendency to respond “change” under the Irrelevant-change condition (0.28) than the No-change condition (0.44). As to RT, although Experiment 3 exhibited a tendency for quicker response relative to Experiment 2’s dual-task condition, the main effect of Condition did not reach significance, F(1, 26) = 3.41, p > 0.075, \( \eta^2_p = 0.12 \). However, similar to criterion, a significant main effect of Change-type was revealed for RT, F(1, 26) = 16.70, p < 0.01, \( \eta^2_p = 0.39 \), indicating that RT was delayed under Irrelevant-change (796 ms) relative to No-change (762 ms). Importantly, in line with the previous two experiments, the Change-type by Condition interaction was not significant on d’ (F < 1), criterion, F(1, 26) = 1.76, p = 0.20, \( \eta^2_p = 0.06 \), or RT, F(1, 26) = 1.31, p = 0.26, \( \eta^2_p = 0.05 \), suggesting that OBE occurred equally in the dual-tasks conditions of Experiments 2 and 3; these results provide further evidence supporting robust OBE.

General discussion

The goal of current study was to investigate whether robust or weak OBE exists in VWM. There are three critical differences between the studies supporting robust OBE and the ones supporting feature-based encoding or weak OBE. In three experiments, we examined the three possible factors, each of which may erase OBE and thereby support the weak OBE hypothesis. Experiment 1 examined whether long exposure time to the memory array allowed top-down control to erase OBE. Experiments 2 and 3 examined the combined influence of task instruction, change rate of the irrelevant feature, and the amount of resources available for processing of the irrelevant feature. We found that none of these factors affected OBE by revealing similar irrelevant-change distracting effects between the experimental condition (which manipulated these factors) and the control condition. Together, these findings suggest that OBE—which occurs during the initial processing stage of VWM—is a very robust processing manner.
Previous findings demonstrated that exposure time to the memory array modulated the distracting effect caused by the irrelevant information (Sander et al., 2011b). In particular, the distracting effect is gradually reduced as the exposure time increases from 100 to 1000 ms; in young adults, the distracting effect is not even observable after the long exposure time (1000 ms). In contrast to that finding, Experiment 1 revealed similar distracting effects between 100 and 1000 ms. As mentioned previously, 1000 ms exposure time is sufficient to allow relatively slow top-down control to interact with the stored representation in VWM. Therefore, the results of Experiment 1 suggested that OBE is fairly robust because it could not be reduced by top-down control. Moreover, the results of Experiment 1 imply that the absence of OBE in Serences et al. (2009) is not related to the long exposure time to the memory array but to some other factors. For instance, the relevant and irrelevant features in the tested materials could not be combined into one object in nature (see the General Discussion in Gao et al., 2010 for details). The discrepancy in results between the current study and the previous study (Sander et al., 2011b) might be due to the different types of distracting information explored between the two studies. Specifically, the targets and distractors were displayed in different locations in the study by Sander et al. (2011b); however, they shared the same spatial locations in the current study. In the former condition, the participants filtered distracting information according to locations (and feature-dimensions), while in the current condition, the participants filtered distracting information on the basis of one specific feature-dimension. Some evidence suggests differences in the information-selection mechanisms employed between the two conditions (Chen, 2003; Yin, Zhou et al., 2012; Zhou et al., 2011). Therefore, it is possible that the failure of the exposure-time manipulation to erase OBE in Experiment 1 is related to the processing characteristics of feature-based selection or filtering.

Like the results of Experiment 1, those of Experiments 2 and 3 support the robust OBE hypothesis. Although we exerted three substantial changes to the experimental settings, which may significantly influence the processing manner (particularly in Experiment 3), these manipulations failed to erase OBE. Instead, the distracting effect was akin to that observed in our previous studies (Yin, Zhou et al., 2012) and the current control block (the single task of Experiment 2). On the one hand, these results confirm our recent claim that OBE also takes places in high-VWM-load conditions (Yin, Zhou et al., 2012); on the other hand, together with the findings of Experiment 1, these results suggest that the “irrelevant-change distracting effect” is fairly sensitive in revealing the extraction mechanism of VWM. The previous studies’ failure to reveal OBE of irrelevant simple features might have been caused by the insensitive task manipulations used (see also the Discussion in Gao et al., 2010; Yin, Zhou et al., 2012).

Taken together, these results might lead one to ask what leads to the robustness of OBE in VWM. There are at least two possible explanations. First, separate storage spaces may exist for distinct simple features (Wheeler & Treisman, 2002); this contention has received support from two recent studies (Bays, Wu, & Husain, 2011; Fougnie & Alvarez, 2011). Using different manipulations, researchers have consistently found that for bars containing simple colors and orientations, the storage spaces for each attribute are independent of each other; this finding runs contrary to the prediction of object-based storage that the memory/report errors for color and orientation should be correlated. However, this explanation alone cannot explain OBE: if this explanation exclusively determined OBE, then the participants should also be able to select distracting information distributed onto distinct locations from the targets into VWM. How-
ever, Vogel, McCollough, and Machizawa (2005) have provided compelling evidence suggesting that—at least for high-VWM-capacity participants—this type of distracting information is not selected for entry into VWM. Second, since simple features are processed at a pre-attentional level at the perceptual stage—the output of which is an integrated proto-object (Ullman, 1984; Wolfe & Bennett, 1997)—the human vision system can easily extract them into VWM without additional cost. Indeed, our previous study found no difference in consolidation rate between objects containing one and two simple feature-dimensions (Gao et al., 2011). Facing this situation, if we intend to select only one feature dimension for entry into VWM, then we first decompose the coherent perceptual object into its separate features (i.e., reverse the binding process), which is a resource- and time-consuming process. Consequently, the visual system adopts a more economical way to extract perceptual information into VWM, albeit after which multiple-featured object representations may be decomposed into their separate features (Bays et al., 2011; Fougnie & Alvarez, 2011).

Conclusion

In three experiments, we demonstrated that OBE was stable in the VWM encoding phase, even in harsh conditions, which could potentially prevent this processing manner. Therefore, a robust OBE hypothesis is supported; that is, irrelevant, high-discriminable information always enters VWM automatically along with the target information.

Keywords: irrelevant-change distracting effect, object-based encoding, visual working memory

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Footnote

1 We also conducted mixed ANOVAs with Change-type as a within-subjects factor and Condition (Experiment 2 single task, Experiment 2 dual tasks, and Experiment 3) as a between-subjects factor on d’’, criterion, and RT. No significant Change-type by Condition interaction (all p-values >0.2) was revealed in any of the three indices, consistent with the current claim.

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Corresponding author: Zaifeng Gao.
Email: zaifengg@zju.edu.cn.
Address: Xixi Campus, Zhejiang University, Hang Zhou, P.R. China.
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