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Electrophysiological evidence of object processing in visual working memory

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Abstract
There is an ongoing debate concerning object-based or feature-based processing when objects are stored in visual working memory (VWM). The present study demonstrates that object processing depends not only on the irrelevant features but also on the number of objects to be remembered. In a change-detection paradigm, participants were asked to memorize two, four, or six object colors for later detection and ignore the object shapes. The processing of task-irrelevant shapes was evaluated. The results of Experiment 1 showed that object-based processing dominated in visual working memory when memory load was two or four, but feature-based processing took over when the memory load was six, as indicated by the N2pc potentials. Experiment 2 used detailed random polygons that were defined by color and shape as memory items. The level of memory load was limited to two and four colors. The results showed that the N2pc potential only appeared in the color-matched condition and was not affected by memory load, suggesting that feature-based processing dominated whenever the task demand was low. These results support the notion of a discrete model of object processing in visual working memory that allocates discrete mechanism for different features. Furthermore, our study highlights the relationship between working memory resources and object processing in visual working memory.

Keywords: visual working memory, memory load, event-related potential, N2pc.

Introduction

Visual working memory (VWM) enables the online maintenance and manipulation of a limited amount of visual information (Irwin & Andrews, 1996; Vogel & Machizawa, 2004). Previous studies have shown that VWM capacity is limited to approximately three or four representations (Bays & Husain, 2008; Vogel, Woodman, & Luck, 2001; Oberauer & Eichenberger, 2013). Thus, to accomplish the current task efficiently, selection of task-relevant information and suppression of task-irrelevant information is of great importance (Chun & Potter, 1995; Schmidt, Vogel, Woodman, & Luck, 2006).

However, everyday objects that are stored in VWM are usually consist of various feature properties. Whether observers could voluntarily encode and store a single property of an object without obligatorily encoding and storing all of an object's features into VWM still remains unresolved. Two theories of object processing in VWM have been proposed to investigate the question: feature-based and object-based processing (Treisman & Gelade, 1980; Parra, Cubelli, & Della Sala, 2011; Woodman & Vogel, 2008). Researchers who support feature-based processing postulate that individuals are able to decide which features of an object are stored in VWM rather than automatically process the integral object (Ueno, Mate, Allen, Hitch, & Baddeley, 2011). Proponents of object-based processing, however, suggests that when one object feature is paid attention, other features may also be processed, even when these task irrelevant features (Luria & Vogel, 2011). Both feature-based and object-based theories are supported by a number of studies (Luck, Girelli, McDermott, & Ford, 1997; Parra, Cubelli, & Della Sala, 2011; Shen, Tang, Wu, Shui, & Gao, 2013; Woodman & Vogel, 2008). Thus, the question on how we control which features are held in VWM is still under debate.

To reconcile the two seemingly contradictory theories mentioned above, Shen et al. (2007) proposed a discrete model of VWM storage, which proposes that simple irrelevant object features, such as color and shape, are stored as an integrated object in VWM, whereas detailed irrelevant features like changes in color, shape, or orientation are difficult to store as an integrated object. The authors further explained that features are maintained in VWM via two distinctive mechanisms. Simple features processed in parallel during the perceptual processing stage are easily stored along with relevant features in VWM, even when these features are task irrelevant. On the other hand, detailed features processed serially during the perceptual processing stage are not easily stored as an integrated object (Gao, Gao, Li, Sun, & Shen, 2011; Shen et al., 2007; Shen, Tang, Wu, Shui, & Gao, 2013). The discrete model of object processing in VWM integrates the alternative accounts of object-based and feature-based processing to some extent, and was further examined by several studies (Gao, Li, Yin, & Shen, 2010; Olson & Jiang, 2002). However, the processing materials used in these studies did not engage purely visual object working memory but a mixture of visual object and spatial working memory. Researchers proposed that Visual object working memory and visual spatial working memory operate separately (Vicari, Bellucci, & Carlesimo, 2006). Thus, the discrete model of object processing in VWM needs further exploration to disambiguate the effects of object and spatial working memory.

Although the discrete model describes storage processing in VWM clearly, it is uncertain whether the model applies to all conditions, and whether storage processing in the discrete model is modulated by other factors. There is considerable behavioral and neurophysiological evidence that object-based processing is determined by the encoding situation of target features (Bays, Wu, & Husain, 2011; Xu, 2010). Therefore, storage processing in VWM not only may depend on the type of irrelevant feature but also may closely correlate with VWM resources. However, others have demonstrated that object-based encoding in VWM was robust even under difficult conditions and could not be affected easily (Ecker, Maybery, & Zimmer, 2013). Whether object processing is modulated by VWM load therefore needs further investigation.

he present study aimed to re-examine the discrete model of object processing in VWM proposed by Shen et al. (2007) and to investigate the relationship between VWM resources and object processing using the event-related brain potential (ERP) component N2pc. The N2pc is an electrophysiological marker for the allocation of VWM resources that is usually elicited at posterior electrodes contralateral to the visually presented task-relevant stimuli between 180 and 300 ms after target appearance (Kiss, Van Velzen, & Eimer, 2008). The N2pc is an enhanced negativity component that indexes the amount of attention deployed to a stimulus; its latency corresponds to the point in time of attentional deployment (Brisson, Robitaille, & Jolicoeur, 2007; Eimer & Kiss, 2008).

We assume that object-based processing dominates when the irrelevant feature consists of simple shapes and N2pc amplitudes elicited by both color and shape are observed, but feature-based processing is indicated when the irrelevant feature consists of detailed shapes, as indicated by the N2pc only found in color-matched condition rather than shape-matched condition. Furthermore, object processing is expected to be modulated by memory load. When VWM resources are scarce, even simple irrelevant features cannot be processed along with relevant features in VWM, which was indicated by the various N2pc potentials in different memory load.

Method

Experiment 1

Participants

Eighteen neurologically unimpaired undergraduate volunteers (eight men, ten women; Mage = 22.1 years, age range = 21–26 years) participated in Experiment 1. All participants were right-handed and had normal or corrected-to-normal vision. More importantly, no participant has color blindness. The experiment was approved by the ethics committee of the School of Psychology, Southwest University.

Design

The probe type (target feature match: color-match, irrelevant feature match: shape-match) and memory load (two, four, or six items; corresponding to low, medium, or high memory load, respectively) were manipulated within participants. There were 900 randomly ordered trials in total, 150 for each condition. All trails were divided into nine blocks, and each block consisted of 100 trials. Participants do not start formal experiments until reached 75% accuracy in practice trials.

Materials

Seven distinct colored shapes were chosen from the study of Xu and Chun (2006). The memory display consisted of two, four, or six colored shapes chosen randomly from a set of 49 shapes. All displays subtended an area of 4.78° × 4.78° of visual angle and were centered on a black background.

Procedure

A example of a single trial is depicted schematically in Figure 1. After a 500–1000 ms fixation period, the memory array containing two, four, or six colored shapes, for 200 or 400ms (In order to insure the similar difficulty, duration was 200ms when the load was two and four but 400 ms when six) was presented. Later, a 1000-ms blank interval was set. The test array was then displayed until paticipate make a response. Participants was required to focus on detecting a color change and to ignore the shapes. All different colored objects had an equal chance of appearing. Colors in the memory and test displays were same in 50% of the trials (color-matched condition), and on the other 50%, the color of one item in the test array changed compare with the corresponding item in the memory display, but the shapes were not changed (color-mismatched but shape-matched condition). No trials where both color and shape were changed were presented. Participants were instructed to press one of the two buttons ("F" and "J" on the keyboard) on each trial. When colors of the memory and test arrays were identical, they should press "F" as soon as they perceive, otherwise, "J" on the keyboard should be pressed. Response accuracy and reaction times (RT) during the experiment were collected.

Results

Behavioral results

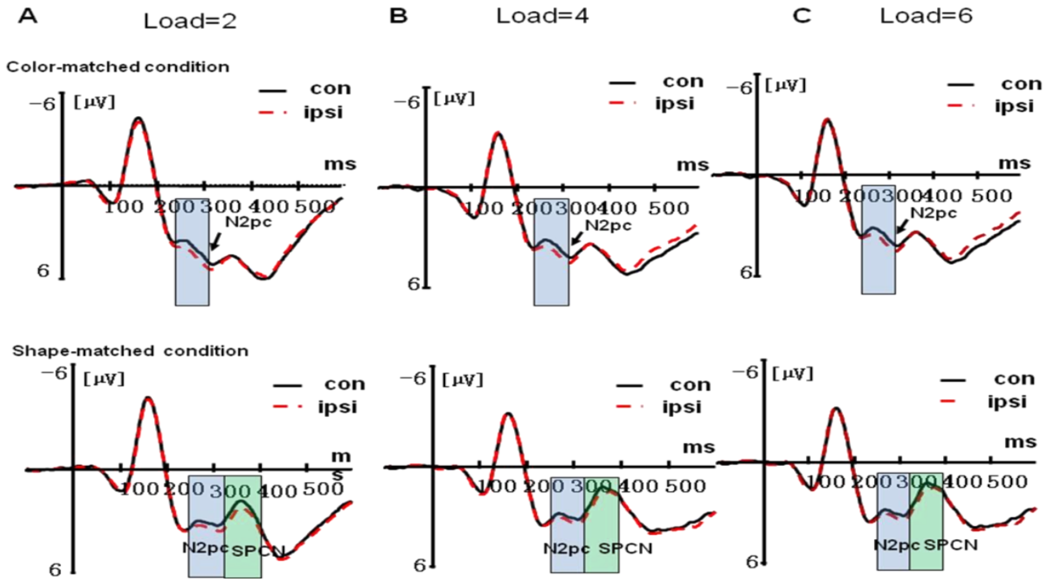
Trials with RTs exceeding three SDs for each participant's grand mean were excluded from the analyses. Table 1 shows the mean RTs and accuracy (proportion of correct responses) in each condition.The mean RTs and accuracy were subjected to a 2 × 3 (Probe type [color, shape] × Memory load [two, four, six] repeated-measures ANOVA respectively. For RTs, the ANOVA revealed significant main effects of load, $F(2, 17) = 59.09$, $p < .01$, $\eta 2p = .77$, and probe type, $F(1, 17) = 11.72$, $p < .01$, $\eta 2p = .41$. The interaction between those two factors was also significant, $F(2, 17) = 33.35$, $p < .01$, $\eta 2p = .66$. Pairwise comparisons showed that RTs for color-matched trials were faster than for shape-matched trails when the memory load was four ($p < .05$) and six ($p < .001$), while responses to color and shape did not differ when the load was two. For accuracy, a significant main effect was found on load, $F(2, 17) = 81.46$, $p < .01$, $\eta 2p = .82$, indicating that mistakes were made more easily in the high-load condition. No other significant effects were observed.

ERP results

Figure 1 illustrates the ERPs elicited by targets in all conditions at the PO7/8, PO3/4, P7/8, and O1/2 electrodes.The ERP amplitudes were analyzed with a 2 × 2 × 3 (Laterality [contralateral, ipsilateral) × Probe type [color, shape] × Memory load [two, four, six] repeated-measures ANOVA separately for the 240–320 ms (late N2pc) and the 320–400 ms (SPCN) analysis windows. In the 240–320 ms time window, a significant main effect of laterality was found, $F(1, 17) = 24.91$, $p < .001$, $\eta 2p = .59$, demonstrating the presence of the later N2pc in the contralateral hemisphere. We also found a significant main effect of probe type, $F(1, 17) = 38.78$, $p < .001$, $\eta 2p = .70$, indicating that the N2pc amplitude was larger for color-matched trials than for shape-matched trials. No other main effects or interactions were found.

A 2 × 3 (Probe type [color, shape] × Memory load [two, four, six)] repeated-measures ANOVA was further conducted on the N2pc amplitudes, revealing no significant main effects or interactions. Simple t-tests revealed that the amplitude differences between contra- and ipsilateral hemisphere electrodes were significant in both color-matched and shape-matched conditions when the working memory load was two (c2 and s2, respectively), $t(c2) = -4.71$, $p < .01$, $t(s2) = -3.7$, $p < .01$, or four (c4 and s4, respectively), $t(c4) = -2.41$, $p < .05$, $t(s4) = -2.60$, $p < .05$, indicating the appearance of N2pc. However, when the memory load was six, the N2pc difference appeared only in the color-matched condition, $t(c6) = -2.49$, $p < .05$, but not in the shape-matched condition, $t(s6) = .80$, $p > .05$.

Figure1



In the 320–400 ms time window, there were significant main effects of laterality, $F(1, 17) = 23.03$, $p < .001$, $\eta 2p = .58$, probe type, $F(1, 17) = 54.62$, $p < .001$, $\eta 2p = .76$, and memory load, $F(2,17) = 6.50$, $p < .05$, $\eta 2p = .28$. Further, a significant interaction between laterality and probe type was found, $F(1,17) = 4.78$, $p < .05$, $\eta 2p = .22$. The follow-up comparison demonstrated that contralateral and ipsilateral potentials induced by target color did not differ significantly (Md = -.05, $p = .50$), but the contralateral potential elicited by irrelevant shapes was significantly smaller than the ipsilateral potential (Md = -.30, $p < .001$).

Paired t-tests with memory load (2, 6) as a factor for the difference amplitude between contralateral minus ipsilateral recordings showed that low memory load (2 items) yielded slightly smaller but nonsignificant difference waves compared to the high memory load, $t(2) = -1.93$, $p = .07$, suggesting a modest load modulation effect. When probe type (color, shape) was used as factor for comparing the difference amplitudes, it was further confirmed that difference waves for the irrelevant shape condition were significantly smaller when the load was two, $t= -3.84$, $p < .01$, or four, $t= -3.19$, $p < .01$, but this effect disappeared during the high-load condition. Difference potentials elicited by color did not differ from those elicited by shape for all memory loads, , which confirmed significant laterality effects for irrelevant features but only in the two- and four-load conditions. Thus, laterality effects were absent when the memory load was sufficiently high.

Experiment 2

Participants

Eighteen new undergraduate volunteers (nine men, nine women; $M_{age} = 22.4$ years, age range = 21–26 years) participated Experiment 2. The participant requirements were the same as those described in Experiment 1.

Design

The probe type (target feature match: color-match, irrelevant feature match: shape-match) and memory load (two or four items; corresponding to low or high memory load, respectively) were manipulated factorially within participants, in a two-way repeated-measures design. There were 600 randomly ordered trials in total, 150 for each condition. All trails were divided into six blocks, and each block consisted of 100 trials. Participants do not start formal experiments until reached 75% accuracy in practice trials.

Procedure

A schematic illustration of a single trial is depicted in Figure 1. After a 500–1000 ms fixation period, the memory array containing two or four colored shapes, for 200. followed by a 1000-ms blank interval. The test array was then displayed until a response was initiated. Participants were instructed to focus on detecting a color change and to ignore the shapes. All different colored objects had an equal chance of appearing. In 50% of the trials, colors in the memory and test arrays were identical (color-matched condition), and on the other 50%, the color of one item in the test array was different from that of the corresponding item in the memory array, but the shapes were not changed (color-mismatched but shape-matched condition). No trials where both color and shape were changed were presented. Participants responded by pressing one of the two buttons ("F" and "J" on the keyboard) on each trial to indicate whether the colors of the memory and test arrays were identical.

Results

Behavioral results

Trials with RTs exceeding 3 SDs from the mean for each participant were excluded from analyses. Table 2 shows the mean RTs and accuracy in each condition. Mean RTs and accuracy were examined with a 2 × 2 (Probe type [color, shape] × Memory load [2, 4]) repeated-measures ANOVA, respectively. For the RTs, the analysis revealed a significant main effect of probe type, $F(1, 17) = 5.73$, $p < .05$, $\eta 2p = .29$, and memory load, $F(1, 17) = 40.15$, $p < .01$, $\eta 2p = .74$, but interaction between them was not significant. Further analysis revealed consistently faster responses in the color-matched condition whenever the memory load was two or four. For accuracy, there was only a significant main effect on load, $F(1,14) = 327.60$, $p < .01$, $\eta 2p = .96$. Higher accuracy in low load than in high load.

ERP results

The ERP values were examined with a 2 × 2 × 2 (Laterality [contralateral, ipsilateral] × Probe type [color, shape] × Memory load [two, four]) repeated-measures ANOVA during the 240–320 ms (later N2pc) and 320–400 ms (SPCN) analysis windows. During the 240–320 ms time window, the main effect of laterality was significant, $F(1, 17) = 12.03$, $p < .01$, $\eta 2p = .46$; the interaction between laterality and probe type was also significant, $F(1, 17) = 9.32$, $p < .01$, $\eta 2p = .40$. Pairwise comparisons showed that the amplitude at the contralateral site was significantly smaller than at the ipsilateral site in the color-matched condition but not in the shape-matched condition, suggesting that the N2pc was only apparent in the color-matched but not in the shape-matched condition. No other main or interaction effects were found. T-tests (compare with zero) on N2pc values (Md= Mcontra - Mipsi) in color-matched condition and shape-matched condition were taken. N2pc amplitude was significant smaller than zero in color-matched condition regardless of load, $t(c2) = -3.73$, $p < .01$; $t(c4) = -3.19$, $p<.01$, However, in shape-matched condition, N2pc value was no significant difference with zero, which further confirmed that attention was deployed only when the target color reappearance rather than irrelevant shape. During the 320–400 ms time analysis window, neither the main effects nor the interactions reached significance.

Discussion

The present study shows that simple irrelevant features are allocated into VWM along with relevant information, confirming an object-based storage system. However, when the current processing demand exceeds the limit of the VWM capacity, individuals can ignore the irrelevant information to ensure the efficiency of the search task. On the other hand, objects consisting of detailed irrelevant features show feature-based storage in VWM. Thus, individuals process only relevant information and ignore detailed irrelevant features. Our study demonstrates that the storage of irrelevant features in VWM depends on perceptual processing and encoding demand of the relevant features.

Although various researchers have explored the processing of object storage in VWM, only a few used the ERP potential N2pc as an indicator. The N2pc specifically demonstrates the allocation of spatially selective attention (Woodman & Luck, 1999). Larger N2pc amplitude means that more attention is deployed (Hickey, McDonald, & Theeuwes, 2006; Luck, 2005b). The latencies of the N2pc reflect the moment when attention is allocated (Brisson, Robitaille, & Jolicoeur, 2007). In our study, we observed that the repetition of relevant and irrelevant features elicited the N2pc. In Experiment 1, using shapes and colors as targets elicited larger N2pc magnitudes when the memory load did not exceed the limitation of VWM. The magnitudes were similar for shapes and colors, suggesting that an object-based storage system exists in VWM. Furthermore, the appearance of SPCN observed between 320 and 400 ms indicated that irrelevant feature shapes not only demanded more attention but were also processed further in VWM. These results are consistent with previous studies (Luck, Girelli, McDermott, & Ford, 1997; Wheeler & Treisman, 2002; Xu, 2010). However, when we showed participants six objects containing color and shape, which exceeded the capacity of VWM, results changed. A larger N2pc was found in the color-matched condition but disappeared in the shape-matched condition. This can be explained by the load theory of selective attention proposed by Lavie and Hirst (2004), who demonstrated that distractor encoding could be impeded when perceptual load of target process increasing(Lavie, 2005). In situations of low-demand encoding, any resouces not used to process task-relevant features would involuntarily “spill over” to the perception of task-irrelevant items. As encoding demand increases, however, relevant processing begins to engage the full VWM capacity, leaving none for processing task-irrelevant features. Thus, under these conditions, objects showed feature-based processing when they were stored into VWM. In conclusion, our behavioral and ERP evidences in Experiment 1 further confirmed that object-based processing in VWM does exist, but is subject to modulation by the memory load of the task-relevant object features.

In Experiment 2, we presented multi-feature objects consisting of colored polygons. Color was the task-relevant feature and the shape of the polygons was the task-irrelevant distractor. Unlike Experiment 1, slower RTs were observed in the shape-matched condition compared to the color-matched condition whenever the memory load was low or high. Measures of N2pc also supported this conclusion by showing that only the color-matched condition induced significant differences in N2pc, indicating that individuals have ability to control what features can be stored in VWM. The only difference between Experiment 1 and 2 was the type of irrelevant feature. Simple shapes are a highly discernible type of visual information that can be processed automatically and in parallel at the perceptual stage (Pasternak & Greenlee, 2005; Wolfe & Horowitz, 2004) On the other hand, a polygon contains more detail that is processed serially at the perceptual stage in a top-down fashion. A previous study suggests that the selection of the irrelevant feature might depend on information type on perceptual stage (Gao et al., 2010). Our experiments further confirmed the hypothesis that there is a dissociated extraction process in VWM.

The results of our discrimination task extend previous results of change detection tasks (Lin & Luck, 2012; Wheeler & Treisman, 2002). On the one hand, previous studies often used objects containing both spatial and object information as experimental stimuli (Gao, Li, Yin, & Shen, 2010; Olson & Jiang, 2002). This combination is questionable when investigating object processing in VWM, because studies have shown that the processing of spatial and object information is separate in VWM (Vicari, Bellucci, & Carlesimo, 2006). Thus, the present study used meaningless polygons to exclude interference of spatial information. On the other hand, measures of N2pc in our study directly probed the effects of attention allocation and the time course of attention shift, which further confirmed the assumption of a discrete storage model, as proposed by Shen et al. (2007).

Conclusion

In summary, the present study found that object-based storage does occur in VWM when the irrelevant features are simple and perceptually processed in parallel. However, this storage was transient and disappeared under a high load processing demand of the task-relevant object feature. Feature-based processing was shown when the irrelevant feature was detailed and perceptually processed in serial. These results suggest that the processing of irrelevant features was not only determined by how those features were processed at a perceptual stage but also by the VWM load of the relevant features.

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