The effect of perceptual interference on prioritization of feature dimensions in visual working memory

Zifang Zhou[1], Lijing Guo[1], Tiina Parviainen[2], Yuxin Cheng[1], Chaoxiong Ye[1,2*]

[1] Institute of Brain and Psychological Sciences, Sichuan Normal University, Chengdu, China;
[2] Department of Psychology, University of Jyvaskyla, Jyväskylä, Finland.

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Abstract

In visual working memory (VWM) tasks, participants' performance can be improved via dimension-based retro-cues, which direct internal attention to prioritize a particular dimension of objects (such as color or orientation) during the maintenance interval. The information prioritized by retro-cues in VWM corresponds to better performance, which is called dimension-based retro-cue benefit (RCB). In general, RCB is a stable phenomenon that emerges under varied stimulus configurations and timing parameters. The purpose of the present study was to investigate dimension-based RCB's susceptibility to perceptual interference to determine the requirements of attention for cue use. In Experiment 1, participants completed change-detection tasks, and in Experiment 2, we used a recall task to explore the effect of interference on dimension-based RCB. RCB was found in both experiments, but perceptual interference impaired the process of prioritizing dimensional features only in the orientation reports of Experiment 2. We conclude that internal attention can be prioritized to remember specific dimensional features in VWM. Importantly, the process of prioritizing internal attention on a particular dimension in a VWM task is robust and not susceptible to interference by irrelevant perceptual information, except in specific cases.

Keywords: visual working memory, retro-cue, perceptual interference, dimension

Introduction

Visual information from the outside world is constantly changing, and when it disappears, memories of it are stored in the mind and help humans form coherent perceptions. The memory system that stores visual information transiently is known as visual working memory (VWM). An important part of the human cognitive system, it is associated with a variety of complex cognitive processes, such as reading comprehension, reasoning, and general intelligence (Bull et al., 2008; A. R. A. Conway et al., 2003; Daneman & Carpenter, 1980; Fukuda et al., 2010; Oberauer, 2019). In a typical VWM task, participants are asked to remember a set of stimuli and retain the stimulus content for recognition (Feldmann‐Wüstefeld, 2021; Grubert & Eimer, 2015; Hitch et al., 2020; Liang et al., 2019; Luck & Vogel, 1997) or recall (Arnicane & Souza, 2021; Gunseli et al., 2015; Niklaus et al., 2017; Schneider et al., 2017; Ye et al., 2019; Zhang & Luck, 2008) during the testing phase, after the stimuli have disappeared. This process corresponds to the encoding, maintenance, and retrieval stages of VWM (Baddeley, 2012; Kim, 2019; Maniglia & Souza, 2020; Myers et al., 2015; Vogel & Machizawa, 2004; Yu & Shim, 2017).

Because the capacity of VWM is very limited (Bays & Husain, 2008; Lewis-Peacock et al., 2018; Luck & Vogel, 1997; Ozimič & Repovš, 2020; Schneegans et al., 2020; Vogel et al., 2001; Zhang & Luck, 2011), it is necessary to update VWM content according to task requirements. In recent years, it has been shown that internal attention can be directed to information generated or maintained internally in the absence of corresponding perceptual input, such as a particular object or dimension of a VWM representation, yielding better memory performance (Griffin & Nobre, 2003; Landman et al., 2003; Niklaus et al., 2017; Ye et al., 2016). Depending on the priority of the information, internal attention can pick out relevant inputs and disregard irrelevant ones, thus flexibly adjusting the VWM storage content (Atkinson et al., 2018; Bahle et al., 2018; Berryhill et al., 2012; Carrasco, 2011; Hitch et al., 2020).

In a VWM task, attentional selection of memory content after perceptual input is typically examined using retro-cues that are presented during the maintenance stage of the VWM task and that prioritize information by cueing a specific object or dimension (Gunseli et al., 2015; Hajonides et al., 2020; Souza & Oberauer, 2016; van Moorselaar et al., 2015; Ye et al., 2021). In VWM paradigms, retro-cues are a versatile tool to make the concept of attentional focus in VWM empirically tractable (Oberauer & Hein, 2012; Souza & Oberauer, 2016). In the maintenance stage, the information prioritized via retro-cues in VWM corresponds to better performance (e.g., trials with valid retro-cues yield faster response time and higher accuracy in change-detection tasks or smaller errors in recall tasks compared to trials without valid retro-cues), which is called retro-cue benefit (RCB). The acquisition of RCB indicates that internal attention can flexibly select the information of VWM (Delvenne & Holt, 2012; Gilchrist et al., 2016; Griffin & Nobre, 2003; Landman et al., 2003).

Depending on their content, retro-cues can be classified as object-based or dimension-based retro-cues (Ye et al., 2016). Object-based retro-cues point to one or more specific memory objects at the same time; they include cues that indicate the location of the target object (e.g., left or right) (Kuo et al., 2011; Lepsien et al., 2005; Matsukura et al., 2014; Matsukura & Vecera, 2015; Murray et al., 2013; Myers et al., 2015) and cues that indicate a specific feature of the target object (e.g., red or square) (Gilchrist et al., 2016; Heuer & Schubö, 2016; Li & Saiki, 2015; Pertzov et al., 2013; Poch et al., 2017). Dimension-based retro-cues, by contrast, direct attention to one visual dimension of all the memory items (e.g., color, orientation) instead of to a specific object (Hajonides et al., 2020; Maniglia & Souza, 2020; Niklaus et al., 2017; Park et al., 2017; Sasin & Fougnie, 2020; Ye et al., 2016, 2021).

The two types of retro-cues correspond to different internal attention processes. Object-based retro-cues shift internal attention from a distributed mode to a focused mode, which prioritizes the target object and reinforces its representation (Kuo et al., 2011; Lepsien et al., 2011; Nobre, 2008; Souza et al., 2014); dimension-based retro-cues, on the other hand, direct internal attention to one dimension common to all the objects, prioritizing the dimensional aspect of VWM representations (Hajonides et al., 2020; Niklaus et al., 2017). Object-based attention reduces memory load in VWM by prioritizing one of the multiple representations, but dimension-based attention cannot reduce memory load, only the amount of information to be retained in each representation. Using these two kinds of cues helps researchers establish a more complete picture of the impact of internal attention on VWM. Studies using either object-based or dimension-based retro-cues have yielded robust RCB (Matsukura & Vecera, 2015; Park et al., 2017; van Moorselaar et al., 2015; Ye et al., 2016), which means that both types of internal attention can select and prioritize the VWM content. To the best of our knowledge, although many studies have investigated the mechanisms of object-based RCB (Makovski & Jiang, 2007; Niklaus et al., 2017; Rerko & Oberauer, 2013; Souza et al., 2014, 2016; Williams et al., 2013; Matsukura et al., 2007; Pertzov et al., 2013), researchers have devoted very little attention to the mechanisms of dimension-based RCB.

Attention is a property of a variety of perceptual and cognitive operations (Chun et al., 2011), and the same is true of the process of internal attention, which selects memory content. In addition to VWM encoding of to-be-learned material, at least three processes are necessary to generate RCB: (1) encoding and interpreting the cue, (2) reallocating attention according to the cue, and (3) retrieving and reinforcing the representation of the object or dimension cued by the retro-cue from VWM. The latter two processes are essential to eventually determining the existence of RCB (Janczyk & Berryhill, 2014). The processes associated with dimension-based retro-cues—reallocating attention and retrieving representations—may require more attentional resources than do the processes associated with object-based retro-cues, because dimension-based retro-cues only reduce the amount of information to be retained in each representation but cannot reduce memory load. Because attentional response selection is typically assumed to be a constraint of limited capacity (Chun et al., 2011; Pashler et al., 2001; Pashler & Johnston, 1989), it may not be robust. Previous studies have shown that recently encountered information, such as perceptual interference, can impact the deployment of selective attention (Gao et al., 2016; Kiyonaga & Egner, 2016; Olivers, 2009). Thus, there are reasons to believe that dimension-based RCB is susceptible to perceptual interference that appears after the cue.

The purpose of this study was to investigate whether perceptual interference impairs dimension-based RCB in VWM. However, perceptual interference can also influence the consolidation of VWM, thus further impairing the representation of the information maintained in working memory (Barth & Schneider, 2018; Lepsien et al., 2005; Makovski &

Jiang, 2007; Sligte et al., 2008; Souza et al., 2016; van Moorselaar et al., 2015). To rule out this possibility, it was necessary to ensure that the subjects finished the consolidation-of-memory items before the interference appeared. Vogel and Woodman (2006) presented a visual array of colored squares to be remembered and then varied the time until a masking stimulus was presented. The deficit in performance caused by the mask was related to its temporal proximity to the memory item. Longer delays before the presentation of the mask resulted in better performance. The study's results suggested that consolidation is a relatively rapid process; the rate of consolidation was approximately 50 ms per item (Vogel et al., 2006). Later research has suggested that this working-memory-consolidation process takes no more than one or two seconds (Cotton & Ricker, 2022; Nieuwenstein et al., 2009; Nieuwenstein & Wyble, 2014; Ricker & Hardman, 2017; Ricker & Sandry, 2018). To prevent the perceptual interference from interfering with VWM consolidation, the present study used 2000-ms stimulus onset asynchrony between memory-stimuli presentation and perceptual interference. In the present study, perceptual interference consisted of graphic masking of the same category as the memory array. The neutral-cue condition was set as the baseline; by comparing VWM performance under masked and no-mask conditions with a neutral cue, we could ascertain whether perceptual interference impaired VWM consolidation. If graphic masking does not influence the consolidation process, there is no difference between masked and no-mask conditions in the neutral-cue condition.

It should be noted that the main purpose of our experimental design was to investigate whether dimension-based retro-cues can be impaired by perceptual interference. In Experiment 1, the participants performed a change-detection task with dimension-based retro-cues. First, we expected to replicate the findings of previous studies of dimension-based RCB (Hajonides et al., 2020; Niklaus et al., 2017; Park et al., 2017; Sasin & Fougnie, 2020; Ye et al., 2016, 2021), which have found significant dimension-based RCB at a population level (using the mean performance of the sample). More importantly, because previous studies have found that perceptual interference impacts attention to the selection process (Gao et al., 2016; Kiyonaga & Egner, 2016; Olivers, 2009), we tentatively hypothesized that dimension-based retro-cues can be impaired by perceptual interference. Namely, we expected to find that

VWM performance under a masked condition would be worse than that under a no-mask condition in the presence of a valid cue.

Experiment 1

Method

Participants

In total, 24 participants (15 female and 9 males; mean age: 19.9 years; age range 18–23 years) were recruited. They were college or postgraduate students and volunteered to participate in the experiment. All the participants reported having normal or corrected-to-normal vision and no history of neurological problems, and they provided written informed consent before participating in the study. The participants were monetarily compensated for their participation in the experiment. Our study was approved by the ethical committee of Sichuan Normal University. All the study's procedures complied with the Declaration of Helsinki (2008).

Materials and apparatus

The experiment comprised four successive stages: memory array, cue, mask array, and test array. In the memory array, the stimuli were colored arrows with a specific orientation, each 1.2° in length and 0.6° in height. We used eight colors (RGB): orange (249, 166, 10), pinkish-purple (221, 160, 220), magenta (255, 20, 148), green (128, 255, 0), dark yellow (160, 82, 46), dark blue (2, 4, 148), sky blue (0, 191 ,254), and dark green (59, 98, 96). We used eight orientations: 15°, 60°, 105°, 150°, 195°, 240°, 285°, and 330°. Two stimuli were randomly selected and presented on a gray (128, 128, 128) background, which was located on either side of the central fixation point (a black cross) and at 1.5° from the central fixation point. In the cue array, the valid cue was the word "color" or "orientation," which indicated to the participants which of these two dimensions would be tested. The neutral retro-cue was the word "all," which indicated to the participants which both dimensions would be tested. All the words were presented in Chinese. The retro-cues were presented in the center of the screen. In the mask array, the mask pattern was eight colored arrows (0.6° × 0.6°) that intertwined in different orientations; the angle between colored arrows was 45°. The color of the arrow was selected from the color of the memory item array, with a total of 18 mask patterns randomly generated. The test array consisted of the central fixation point and test items that appeared randomly on either side of this point. There were two types of test item. The first was the color-dimension test: the circle with color. On half of the trials, the tested color was identical to the one presented in the memory array at the same location (i.e., no change). On the other half of the trials, the tested color was a new color that did not appear in the memory array (i.e., change). The second was the orientation-dimension test: the arrows with orientations. On half of the trials, the tested orientation was identical to the one presented in the memory array at the same location (i.e., no change). On the other half of the trials, the tested orientation was a new orientation that did not appear in the memory array (i.e., change). The entirety of the experiment was conducted in a softly lit, soundproof room with 19-inch screens (1280 × 768) presenting the stimuli. The distance between the participants and the screen was approximately 60 cm.

Procedure

The experiment procedure is shown in Figure 1. Each trial began with the central fixation point (a black cross) appearing on the screen for 1,000 ms, and the participants were asked to keep their eyes on the position of the black cross throughout the experiment. The memory array was then presented for 150 ms, and the participants were asked to remember the color and orientation of the two arrows on the screen. The color and orientation values were pseudo-randomly selected in each trial, independently for each arrow. After a 700-ms blank, the retro-cue was presented for 400 ms. Half of the trials presented a valid cue that indicated with 100% validity which of the dimensions (color or orientation) would be tested, and half of the trials presented the neutral cue. After the cue, following a 1000-ms blank, the mask array appeared for 100 ms on the site of the memory array to introduce irrelevant information intended to interfere with memory maintenance. Half of the trials contained the mask array, whereas the other half presented the black cross for 100 ms instead of the mask array. After a 400-ms blank, the test array was presented for 2,500 ms, and the participants were asked to indicate whether the color or orientation in the test array was the same as that in the specific location in the memory array. The participants were asked to press “F” on the keyboard to indicate “same” and “J” to indicate “not the same response,” stressing accuracy rather than response speed. The test array disappeared when the participant responded, on half of the trials, the tested array was color-dimension test, on the other half of the trials, the tested orientation-dimension test. During the practice phase, participants were given feedback on their performance; there was no feedback phase in the formal experiment.

The task consisted of 320 trials divided into four blocks of 80 trials (validly cued masked block, validly cued no-mask block, neutrally cued masked block, and neutrally cued no-mask block). The trials were fully randomized. Each participant completed the one-hour task for a total of 320 trials. A short break was provided after 80 trials.

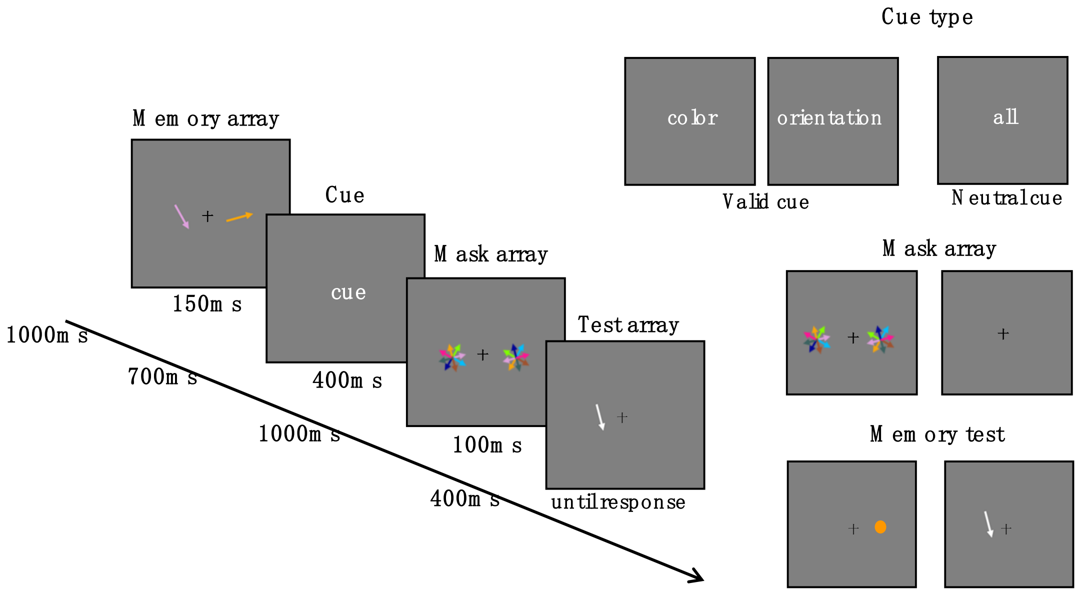

Figure 1 Flowchart of the change-detection task. Each trial begins with the presentation of a fixation cross, then participants need to remember the color and orientation of two arrows until a retro-cue informs participants to keep in memory either color, orientation, or both dimensions. After the cue, the mask array appeared on the site of the memory array. Then the participants were asked to judge whether the color or orientation in the test array was the same as that in the specific location in the memory array.

Data Analysis

To examine whether the use of dimension-based retro-cues is influenced by interfering information, the accuracy (ACC) and d-prime scores [d' = Z (hit rate) - Z (false alarm)] were applied as indices of sensitivity to change detection and were tested using a multiple 2 (neutral cue or valid cue) × 2 (masked or no mask) repeated-measures analysis of variance (ANOVA) with adjustments. A separate ANOVA was conducted for each dependent variable. Significant interactions and main effects were decomposed using Bonferroni corrected pairwise comparisons. Paired-samples t-tests and Bayes factor analysis were conducted to analyze differences in cue efficiency and examine differences in cue efficiency between the masked and no-mask conditions.

Results

Accuracy

Figure 2 shows the ACC score for each cue condition (neutral or valid) in both the masked and no-mask conditions. The multiple 2 (neutral cue or valid cue) × 2 (masked or no mask) repeated-measures ANOVA indicated no significant interaction between the cue condition and mask condition (F (1,23) = 0.197, p = 0.661, η_p^2 = 0.008) and no significant main effects of the mask condition (F (1,23) = 2.455, p = 1.131, η_p^2 = 0.096), but it indicated significant main effects of the cue condition (F (1,23) = 15.338, p < 0.01, η_p^2 = 0.400).

Follow-up paired-samples t-tests showed that the ACC score under the valid-cue condition was significantly higher than that under the neutral cue condition for the masked condition (t (23) = 2.893, p < 0.01, Cohen's d = 0.442, BF_{10} = 5.719) and for the no-mask condition (t (23) = 3.385, p < 0.01, Cohen's d = 0.349, BF_{10} = 15.528). There was no significant difference between the masked and no-mask conditions for the valid-cue condition (t (23) = 0.853, p = 0.403, Cohen's d = 0.087, BF_{10} = 0.298) or for the neutral-cue condition (t (23) = 1.249, p = 0.224, Cohen's d = 0.144, BF_{10} = 0.429).

d-prime

Figure 2 shows d' for each cue condition (neutral or valid) in both the masked and no-mask conditions. The multiple 2 (neutral cue or valid cue) × 2 (masked or no mask) repeated-measures ANOVA indicated no significant interaction between the cue condition and mask condition (F (1,23) = 0.562, p = 0.461, η_p^2 = 0.024) but significant main effects of the mask condition (F (1,23) = 5.135, p < 0.05, η_p^2 = 0.183) and significant main effects of the cue condition (F (1,23) = 10.617, p < 0.01, η_p^2 = 0.316).

Follow-up paired-samples *t*-tests showed that d' under the valid-cue condition was significantly greater than that under the neutral-cue condition for the masked condition (t (23) = 2.656, p < 0.05, Cohen's d = 0.440, BF_{10} = 3.630) and for the no-mask condition (t (23) = 2.682, p < 0.05, Cohen's d =0.300, BF_{10} = 3.810). There was no significant difference between the masked and no-mask conditions for the valid-cue condition (t (23) = 1.217, p = 0.236, Cohen's d = 0.118, BF_{10} = 0.414) or for the neutral-cue condition (t (23) = 1.883, p = 0.072, Cohen's d = 0.250, BF_{10} = 0.975).

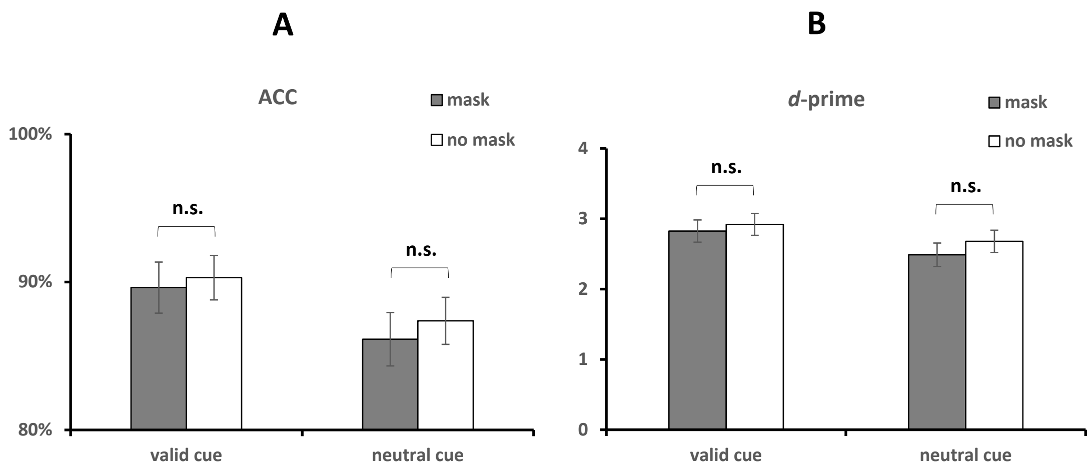

Figure 2 ACC and d-prime results for the masked and no-mask conditions for each cue condition in the color report (n = 24) and average performance across the feature. n.s. = non-significant. Error bars represent ±1 SEM.

Discussion

In Experiment 1, we used a change-detection task and asked the participants to remember two colored arrows. We found that a dimension-based retro-cue can improve the performance of VWM in terms of both the accuracy and response time of participants, indicating the presence of dimension-based RCB. These results demonstrate that participants can use internal attention to select a dimension as a target to improve the VWM representation of the task-relevant dimension in the change-detection task. Notably, VWM representations are not influenced by perceptual interference in the neutral condition, which means that perceptual interference does not influence VWM consolidation. However, it is surprising that there is also no significant difference between the masked and no-mask conditions in the valid-cue condition. This result suggests that dimension-based retro-cues are not susceptible to interference from irrelevant perceptual information in the change-detection task.

Arguably, however, the manner of memory storage employed by participants in the change-detection task influenced the results of Experiment 1. In the change-detection task, which required the participants to remember a sample array of objects over a brief retention interval and then indicate whether any dimension in a subsequent test array had changed, the participants could adjust memory precision when memory load was low. In other words, participants could remember items in either a low-precision or high-precision manner (Gao et al., 2011; Machizawa et al., 2012). If they chose a low-precision manner of storage for memorization, the attentional resources required to remember the same content were lower than those required by the high-precision manner (Ye et al., 2019), thus effectively preventing interference. The results of Experiment 1 show that masking does not interfere with the use of dimension-based retro-cues, possibly due to the low-precision manner of storage adopted by the participants. Preventing participants from selecting a low-precision manner of storage resulting perceptual interference does not affect the process of cue use in masked condition. Therefore, in Experiment 2, we used a recall task that forced the participants to remember in a high-precision manner (Zhang & Luck, 2008) to further investigate whether dimension-based retro-cues could be impaired by perceptual interference.

Experiment 2

The purpose of Experiment 2 was to further investigate whether interference impaired the use of dimension-based retro-cues in VWM. We used a recall task to explore the relationship between irrelevant visual interference and dimension-based RCB. One advantage of this recall task is that it enabled us to measure VWM quality more precisely using the parameter "offset." The recall task of Experiment 2 required participants to select or adjust the color or orientation of the test items during the test phase to remain consistent with their memory. Next, we calculated the offset, that is, the difference between the value chosen by the participants and the memorized item. Another advantage of this recall task is that it enabled us to use model fitting to separate the mnemonic parameters (Bays et al., 2009; Zhang & Luck, 2008, 2009). Consequently, we could unpack the potential sources of dimension-based RCB by using the model in Experiment 2.

Method

Participants

Twenty-four volunteers (19 female and 5 males; mean age: 19.9 years; age range: 18–23 years), all of whom were college or postgraduate students, volunteered to participate in Experiment 2. All the participants reported having normal or corrected-to-normal vision and no history of neurological problems, and they provided written informed consent before participating in the study. The participants were monetarily compensated for their participation in the experiment. Our study was approved by the ethical committee of Sichuan Normal University. All the study's procedures complied with the Declaration of Helsinki (2008).

Materials and apparatus

The experiment consisted of a dimension-based retro-cue recall task. The recall task had four successive stages: memory array, cue, mask array, and test array. In the memory array, the stimuli were colored bars with a specific orientation, each 1.1° in length and 0.4° in height. The color and orientation of each memory stimulus were selected randomly from 360 colors and 180 orientations, respectively. Two stimuli were randomly selected and presented on a gray (128, 128, 128) background, which was located on either side of the central fixation point (a black cross) and at 1.5° from the central fixation point. The dimension-based retro-cues were the words "color" and "orientation," which indicated to the participants which of these two dimensions would be tested. The neutral retro-cue was the word "all," which indicated to the participants which both dimensions would be tested. All the words were presented in Chinese. The retro-cues were presented in the center of the screen. In the mask array, the mask pattern was eight colored bars (1.8° × 0.4°) that intertwined in different orientations; the angle between colored arrows was 45°. The color of the arrow was selected from the color of the memory item array, with a total of 80 mask patterns randomly generated. The entirety of the experiment was conducted in a softly lit, soundproof room with 19-inch screens (1280 × 768) presenting the stimuli. The distance between the participants and their screens was approximately 60 cm.

Procedure

The procedure of Experiment 2 is shown in Figure 3. Except for the test array, the procedure resembled that of the Experiment 1. During the test array, a square was presented on the site of the memory stimulus that was probed. If the color was to be reported, a color wheel was presented together with the square, and the participants were asked to report the color of the memory item by using a computer mouse to select one of the 360 color values on the wheel. If the orientation was to be reported, an adjustable vertical white bar was presented at a fixed point on the screen, and the participants were asked to use the mouse to adjust the orientation of the bar to match the orientation of the memory item. No time constraints were imposed on the participants. After the test array disappeared, feedback on performance accuracy (measured by the deviation of the participant's response from the target stimuli value) was given.

Each task consisted of 800 trials divided into four blocks of 200 trials (validly cued masked block, validly cued no-mask block, neutrally cued masked block, and neutrally cued no-mask block). The trials were fully randomized. Each participant completed two-hour tasks for a total of 800 trials. A short break was provided between blocks.

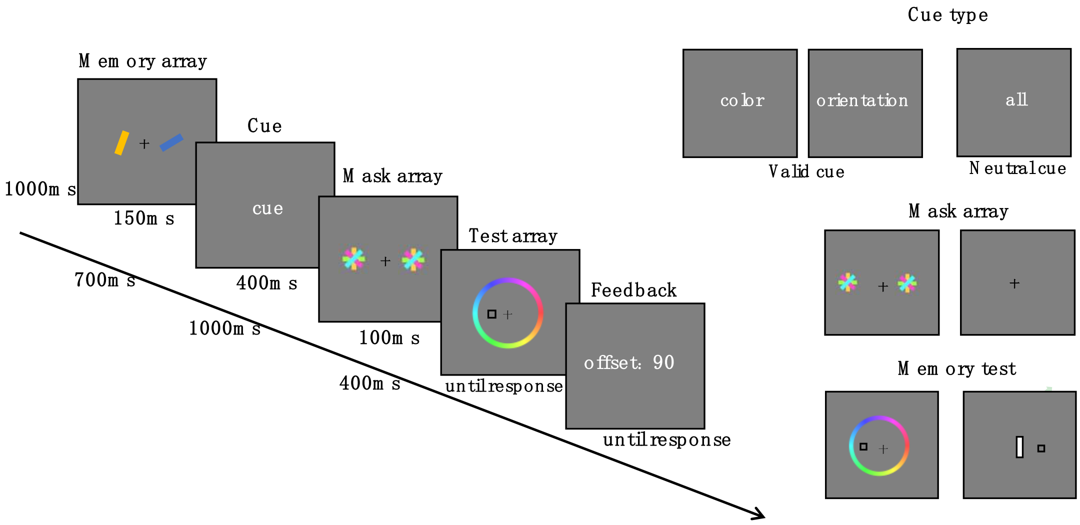

Figure 1 Flowchart of the recall task. Each trial begins with the presentation of a fixation cross, then participants need to remember the color and orientation of two bars until a retro-cue informs participants to keep in memory either color, orientation, or both dimensions. After the cue, the mask array appeared on the site of the memory array. Then the participants were asked to feedback the color or orientation they membered from the memory array in test array. and the test has two conditions. If the color was to be reported, the participants were asked to report the color of the memory item by using a computer mouse to select one of the 360 color values on the wheel. If the orientation was to be reported, the participants were asked to use the mouse to adjust the orientation of the bar to match the orientation of the memory item.

Data Analysis

We obtained the guess rate and standard deviation (SD) index via mixture-model analysis. The model assumes that the distribution of response errors reflects a mixture of two components: (1) a von Mises distribution (the circular analog of the Gaussian distribution) centered on the true feature value for trials in which the probed feature was successfully held in memory and (2) a uniform distribution for trials in which the probed feature was unavailable for the report and a random guess was made. The model has two parameters: SD and the guess rate. The spread of the von Mises distribution is determined by the SD parameter, which is inversely proportional to the precision of the stored representation. The proportional area of the uniform component is determined by the guess rate, which represents the probability that the probed feature was lost from memory. We used the MemToolbox to fit the data for each participant individually for every four conditions, 2 (masked or no-mask condition) × 2 (neutral- or valid-cue condition). Because color and orientation reports in our recall task were different, we analyzed the dependent variables in the color and orientation report trials separately.

The dependent variables were the guess rate, SD, and offset (the deviation of the participant's response from the target stimuli value). To examine whether the use of dimension-based retro-cues is influenced by interfering information, we conducted repeated-measures analysis of variance (ANOVA) for dependent variables with 2 (neutral cue or valid cue) × 2 (masked or no mask) as within-subject factors. Significant interactions and main effects were decomposed using Bonferroni corrected pairwise comparisons. Paired-samples *t*-tests and Bayes factor analysis was conducted to analyze differences in cue efficiency and examine differences in cue efficiency between the neutral-cue and valid-cue conditions. Notably, the offset was defined as the deviation between the target stimuli value and the color step or orientation degree of the participant's response for the color and orientation dimensions, respectively. Because the response ranges of color (1–360 color steps) and orientation (1–180 orientation degrees) differed, the presence of a larger offset in the color-report trials than in the orientation-report trials did not mean that the color-memory performance was worse than the orientation-memory performance. Thus, because the color and orientation reports in our recall tasks differed qualitatively, we conducted separate analyses for the guess rate, SD, and offset RCB in the color- and orientation-report trials.

Results

Color report

Offset. Figure 4A shows the offset for each cue condition (neutral or valid) in both the masked and no-mask conditions. The multiple 2 (neutral cue or valid cue) × 2 (masked and no mask) repeated-measures ANOVA indicated no significant interaction between the cue condition and mask condition (F (1,23) = 0.107, p = 0.747, η_p^2 = 0.005) and no significant main effects of the mask condition (F (1,23) = 0.011, p = 0.916, η_p^2 = 0), but it indicated significant main effects of the cue condition (F (1,23) = 5.561, p < 0.05, η_p^2 = 0.195).

Follow-up paired-samples *t*-tests showed that the offset under the valid-cue condition was significantly greater than that under the neutral-cue condition for the masked condition (t (23) = 2.106, p < 0.05, Cohen's d = 0.269, BF_{10} = 1.382). There was no significant difference between the masked and no-mask conditions for the valid-cue condition (t (23) = 0.368, p = 0.716, Cohen's d = 0.050, BF_{10} = 0.228) or for the neutral-cue condition (t (23) = 0.156, p = 0.877, Cohen's d = 0.023, BF_{10} = 0.217).

Guess rate and SD. Figure 4 shows the guess rate (B) and SD (C) index for each cue condition (neutral cue or valid cue) and for each mask condition (masked and no mask). A larger guess rate and SD index represents worse performance on the recall task. For the guess rate index, the ANOVA results indicated significant main effects of the cue condition (F (1,23) = 5.723, p < 0.05, η_p^2 = 0.199), no significant main effects of the mask condition (F (1,23) = 0.018, p = 0.894, η_p^2 = 0.001), and no significant interaction between the cue condition and mask condition (F (1,23) = 0.11, p = 0.744, η_p^2 = 0.005). Follow-up paired-samples *t*-tests showed that the guess rate under the valid-cue condition was significantly lower than that under the neutral-cue condition for the mask condition (t (23) = -2.210, p < 0.05, Cohen's d =0.303, BF_{10} = 1.640) but not significantly different for the no-mask condition (t (23) = -1.835, p = 0.079, Cohen's d =0.387, BF_{10} = 0.908). There was no significant difference between the masked and no-mask conditions for the valid-cue condition (t (23) = 0.148, p = 0.884, Cohen's d =0.022, BF_{10} = 0.908) or for the neutral-cue condition (t (23) = 0.282, p = 0.780, Cohen's d =0.042, BF_{10} = 0.223).

For the SD index, the ANOVA results showed no significant main effects for the cue condition (F (1,23) = 0.227, p = 0.638, η_p^2 = 0.01) or mask condition (F (1,23) = 0.059, p = 0.81, η_p^2 = 0.003) and no significant interaction between the cue condition and mask condition (F (1,23) = 0.04, p = 0.843, η_p^2 = 0.002).

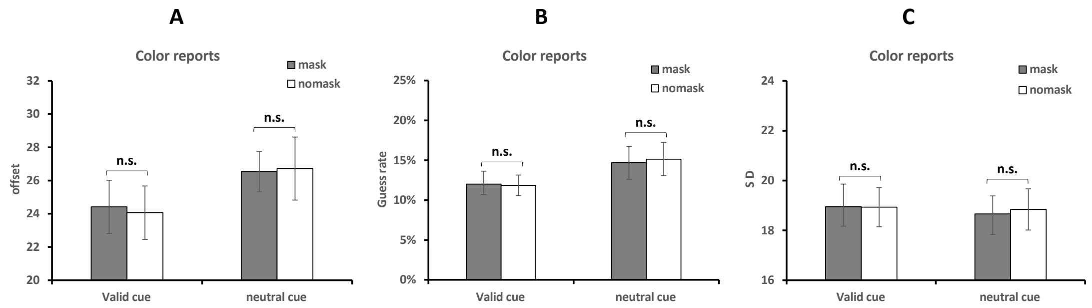

Figure 4 Offset, guess rate, and SD results for the masked and no-mask conditions for each cue condition in the color report (n = 24) and average performance across the feature. n.s. = non-significant. Error bars represent ±1 SEM.

Orientation report

Offset. Figure 5 shows the offset for each cue condition (neutral or valid) in the masked and no-mask conditions. The multiple 2 (neutral cue or valid cue) × 2 (masked or no mask) repeated-measures ANOVA indicated a significant interaction between the cue condition and mask condition (F (1,23) = 5.406, p < 0.05, η_p^2 = 0.190) and significant main effects of the cue condition (F (1,23) = 14.962, p < 0.01, η_p^2 = 0.394) and the mask condition (F (1,23) = 13.724, p < 0.01, η_p^2 = 0.374).

Follow-up paired-samples *t*-tests showed that the offset under the valid-cue condition was significantly greater than that under the neutral-cue condition for the masked condition (t (23) = 2.203, p < 0.05, Cohen's d =0.261, BF_{10} = 1.621) and for the no-mask condition (t (23) = 4.811, p < 0.001, Cohen's d =0.569, BF_{10} = 352.262). There was a significant difference between the masked and no-mask conditions for the valid-cue condition (t (23) = 5.352, p < 0.001, Cohen's d =0.423, BF_{10} = 1180.574) and for the neutral-cue condition (t (23) = 1.314, p = 0.202, Cohen's d =0.130, BF_{10} = 0.460).

Guess rate and SD. Figure 5 shows the guess rate and SD index for each mask condition (masked or no mask) in each cue condition (neutral cue or valid cue). A lager guess rate and SD index represents worse performance on the recall task. For the guess rate index, the ANOVA results indicated no significant main effect for the cue condition (F (1,23) = 1.465, p = 0.238, η_p^2 = 0.06), no significant main effects for the mask condition (F (1,23) = 2.693, p =

0.114, η_p^2 = 0.105), and no significant interaction between the cue condition and mask condition (F (1,23) = 0.222, p = 0.642, η_p^2 = 0.01).

For the SD index, the ANOVA results indicated significant main effects of the cue condition (F (1,23) = 5.534, p < 0.05, η_p^2 = 0.194), no significant main effects of the mask condition (F (1,23) = 0.661, p = 0.425, η_p^2 = 0.028), and no significant interaction between the cue condition and mask condition (F (1,23) = 0.863, p = 0.362, η_p^2 = 0.036). Follow-up paired-samples t-tests showed that the SD under the valid-cue condition was significantly lower than that under the neutral-cue condition for the no-mask condition (t (23) = -2.885, p < 0.01, Cohen's d =0.625, BF_{10} = 5.635). There was no significant difference between the mask and no-mask conditions for the valid-cue condition (t (23) = 1.455, p = 0.159, Cohen's d =0.311, BF_{10} = 0.543) or for the neutral-cue condition (t (23) = 0.084, p = 0.934, Cohen's d =0.017, BF_{10} = 0.215).

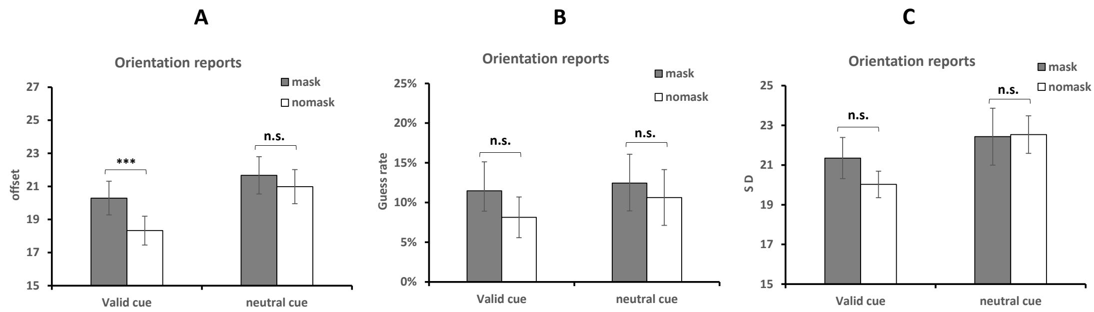

Figure 5 Offset, guess rate, and SD results for the mask and no-mask conditions for each cue condition in the orientation report (n = 24) and average performance across the feature. *** = p < .001; n.s. = non-significant. Error bars represent ±1 SEM.

Discussion

In Experiment 2, we report the color and orientation results separately. The dimension-based retro-cue has improved the performance of working memory for both color and orientation by reducing offset of participants. These results lend further support to the finding that dimension-based retro-cues can improve recall performance, indicating that dimension-based RCB is present in both color and orientation recall. Furthermore, in the color reports, RCB is reflected mainly in guessing-rate reduction. In the orientation reports, RCB is reflected mainly in SD reduction.

The presence or absence of masking does not affect VWM performance in the neutral-cue condition of either color and orientation, which suggests that interfering information does not affect VWM consolidation. More notably, it is only for the orientation report that the results show that the offset of the valid cue is larger than that of the neutral cue in the masked condition, suggesting that masking reduces dimension-based RCB. However, the mixture model for the orientation report does not show that the mask influences the guess rate or SD. A plausible explanation for this finding is that the overall damage imposed by masking on the use of retro-cues observed in the recall offset measure was spread across several parameters such that it could not be credibly ascribed to a particular source.

General Discussion

The present study investigates whether dimension-based retro-cues can be impaired by perceptual interference. Experiment 1 used a change-detection task to investigate this issue. However, the experimental design did not reveal whether perceptual interference impairs the use of dimension-based retro-cues. In Experiment 2, the participants completed a recall task using dimension-based retro-cues with and without interference. The results demonstrate that dimension-based RCB is lower in the masked condition than in the no-mask condition only in the orientation report—not in Experiment 1. This finding suggests that the process of prioritizing internal attention on the memory of the orientation of the two bars in a VWM task is susceptible to interference. However, we find no evidence that this is the case for the color dimension.

Experiment 1 required the participants to remember two arrows over a brief retention interval and then to indicate which dimension would be tested; the participants then judged whether the tested item had changed. Participants can memorize items in a low-precision manner and thereby reduce the cost associated with remembering the same content in a high-precision manner (Gao et al., 2011; Machizawa et al., 2012). In Experiment 2, we used a recall task that forced the participants to remember in a high-precision manner (Ye et al., 2019; Zhang &

Luck, 2008). The results show that dimension-based RCB is impaired by masking, at least in the orientation dimension. One explanation for the divergent results of Experiments 1 and 2 is that the manner of remembering with different precision may affect the process of using retro-cues.

It is a well-established fact that different visual features, such as color, orientation, and spatial frequency, are processed by distinct brain modules (B. R. Conway, 2009; Paik & Ringach, 2011). The different results for color and orientation in Experiment 2 may be due to the differences in how attention works in relation to these two features (Fougnie & Alvarez, 2011; Hubel & Wiesel, 1968; Livingstone & Hubel, 1988; Wang et al., 2017). Specifically, color and orientation are processed by separate neuronal populations (Hubel & Wiesel, 1968; Livingstone & Hubel, 1988), and the perception of orientation is largely independent of the perception of color (Garner, 1974). Color involves a higher-level visual property and may have a more specialized population of neurons. The visual dimension of orientation, by contrast, is much more closely linked to retinal coordinates, and there is no evidence that any specific visual area outside of the primary visual cortex is dedicated to processing this dimension (Niklaus, 2017). Color encoding takes less time than the encoding of orientation (Hao et al., 2018; Miller et al., 2014), and attention to the color dimension will automatically spread to other (uncued) objects(Niklaus et al., 2017). The color and orientation of a multifeature object can be stored separately in VWM (Wang et al., 2017); thus, the intrinsic mechanisms corresponding to internal attention may be different when retro-cues suggest different features, which leads to different effects of interference on the memory of color and the memory of orientation.

In the two experiments, we used a change-detection task and a recall task and found that the dimension-based retro-cues exhibit RCB. Prior studies of dimension-based retro-cues have mainly used recall tasks. Although most studies have supported the existence of dimension-based RCB (Hajonides et al., 2020; Niklaus et al., 2017; Park et al., 2017; Sasin & Fougnie, 2020; Ye et al., 2016, 2021), recent studies have also found a lack of RCB (Maniglia & Souza, 2020; Pilling & Barrett, 2016). Pilling and Barrett (2016) investigated dimension-based retro-cues using a change-detection task, but they did not report the presence of RCB. Their divergent results may be due to that participant needed to switch randomly between the three cues condition (pre-cue, retro-cue, and test cue). This interpretation is supported by a study that used dimension-based retro-cues and task switching between pre-cues and retro-cues; even though it employed a recall task, which usually clearly induces RCB, it observed no RCB (Maniglia & Souza, 2020). These results are in line with the notion that cues that appear at different stages reflect different underlying attentional processes (Chun et al., 2011; Ester et al., 2014; Fougnie & Marois, 2006; Oberauer, 2019; Tsubomi et al., 2013). In future research on robust dimension-based RCB, participants' attentional switching should be reduced to ensure that sufficient attentional resources are allocated to dimension-based retro-cues.

The type of perceptual interference we used deserves further consideration. First, it should be noted that we observed a significant reduction of RCB in the orientation report of the recall task even though our mask could be considered quite simple—at least when compared with the more challenging dual-task interference that object-based retro-cue studies have used (Hollingworth & Maxcey-Richard, 2013; Janczyk & Berryhill, 2014; Makovski & Pertzov, 2015; Rerko et al., 2014). On the other hand, RCB remained evident across all the conditions. Logically, it can be predicted that the reduction in RCB will become even more apparent when a more complex, more attention-demanding task is used. It might even be the case that RCB would be eliminated under such challenging conditions. Future research could use more attention-intensive interference to further investigate its impact on the use of dimension-based retro-cues. Such research would provide a comprehensive understanding of the conditions under which dimension-based retro-cues yield robust RCB.

Conclusion

As a passive form of interference, perceptual interference does not affect the process of prioritizing dimensional features in simple tasks and exhibits interference with the prioritization process only in specific conditions. Specifically, we observed interference impairment of dimension-based RCB only in the orientation report of the recall task, but we found no such impairment in the other conditions.

Author contributions

Zifang Zhou: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing - original draft; Lijing Guo: Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing - original draft; Tiina Parviainen: Writing - review & editing; Yuxin Cheng: Writing - review & editing; Chaoxiong Ye: Conceptualization, Funding acquisition, Methodology, Software, Project administration, Resources, Supervision, Writing - review & editing.

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