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Automatically binding relevant and irrelevant features in visual working memory

Chenxiao Zhao[1], Xinyu Li[1], Michel Failing[2,3] and Benchi Wang[4,5,6,7]

Abstract

It is generally assumed that, to save storage space, features are stored as integrated objects in visual working memory (VWM). Although such an object-based account does not always hold because features can be processed in parallel, a previous study has shown that different features can be automatically bound with their locations (task-irrelevant feature) into an integrated unit, resulting in improved memory performance. The present study was designed to further explore this phenomenon by investigating whether other features, which are not spatial in origin, can act as the binding cue to form such automatic binding. To test this, we used three different features as binding cues (i.e., colour, spatial frequency, and shape) over multiple separate experiments. The results consistently showed that when two features shared the same binding cue, memory performance was better relative to when each of those features had their own binding cue. We conclude that *any* task-irrelevant feature can act as a binding cue to automatically bind with task-relevant features even across different objects, resulting in memory enhancement.

Keywords

Binding; object-based storage; working memory

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Introduction

Visual working memory (VWM) is widely considered a fundamental cognitive system to temporarily maintain visual information for upcoming cognitive tasks (Baddeley, 1992). Because the storage capacity of VWM is limited (Cowan, 2001; Luck & Vogel, 1997), some strategies might be applied to temporarily increase VWM capacity. One of such strategies is described by the object-based storage account according to which binding individual features into integrated objects can result in increased VWM capacity (Awh et al., 2007; Fougnie et al., 2013; Luck & Vogel, 1997; Olson & Jiang, 2002; Vogel et al., 2001; Xu, 2002a, 2002b, 2006).

Early support for the object-based storage account came from Luck and Vogel's (1997) seminal work on VWM capacity. In one of their studies, they asked observers to memorise either all features or just a single feature of each object in an array of multiple-feature objects. Their results showed that memory performance on these objects was statistically indistinguishable between the two conditions suggesting equally efficient encoding (see also Delvenne & Bruyer, 2004; Vogel et al., 2001). While this

[1]Department of Psychology, Zhejiang Normal University, Jinhua, China
[2]Charité—Universitätsmedizin Berlin, Berlin, Germany
[3]Berlin Institute of Health, Berlin, Germany
[4]Key Laboratory of Brain, Cognition and Education Sciences (South China Normal University), Ministry of Education, Guangzhou, China
[5]Institute for Brain Research and Rehabilitation, South China Normal University, Guangzhou, China
[6]Center for Studies of Psychological Application, South China Normal University, Guangzhou, China
[7]Guangdong Key Laboratory of Mental Health and Cognitive Science, South China Normal University, Guangzhou, China

Corresponding authors:
Xinyu Li, Department of Psychology, Zhejiang Normal University, Yingbin Road 688, Jinhua 321004, China.
Email: xyli@zjnu.cn

Benchi Wang, Institute for Brain Research and Rehabilitation, South China Normal University, Zhongshan Road West 55, Guangzhou 510631, China.
Email: wangbenchi.swift@gmail.com

finding supports the idea that individual features are bound into integrated objects, it may equally well be explained by assuming that different features are stored in parallel (see Chen et al., 2021; Fougnie & Alvarez, 2011; Wang et al., 2017; Wheeler & Treisman, 2002). To rule out this alternative explanation, Luck and Vogel (1997, last experiment) showed observers objects consisting of two feature values (e.g., green and red) from the same feature dimension (i.e., colour) as memory stimuli. Yet again consistent with the object-based storage account, they found no evidence for deterioration in memory performance when two features relative to when only a single feature had to be memorised. Although convincing at the time, later follow-up studies could not replicate this critical finding (Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002b). Inconsistent with the object-based storage account, these studies found a deterioration in memory performance when participants had to memorise an array of objects with multiple features from a single feature dimension compared to when they had to memorise the same amount of objects with only a single feature.

Although such an object-based account does not always hold because features can be processed in parallel, Wheeler and Treisman (2002) further investigated whether it is possible to combine two features together to form an integrated unit in a "forced" way. However, instead of an object-based benefit, they found worse memory performance under conditions of feature binding. In their feature-binding condition, to-be-memorised coloured objects either did or did not swap locations between the memory and test display and observers had to indicate whether a swap occurred. Under these circumstances, either memorising colour or location alone would make it impossible to knowingly give the correct response. In other words, observers were forced by the task demands to actively bind colour and location information together to be able to do the task. As a result, memory performance in this feature-binding condition was worse compared to when observers were required to memorise only a single feature. That is, "extra attentional resource" was required in their feature-binding condition, resulting in worse performance.

Note that, however, WM has a limited capacity; binding individual features into a single unit should be a viable strategy to improve memory performance. Indeed, this strategy is largely consistent with the *chunking* strategy as originally proposed by Miller (1956). Through different methods of grouping and organisation, information can be incorporated into one chunk, resulting in more information being memorised. Akin to this idea, it appears feasible to bind features together to improve memory performance rather than reduce performance (as shown in Wheeler & Treisman, 2002). In line with this, a recent study showed that observers could use the location of an object (a task-irrelevant feature) as a binding cue to automatically bind with other task-related features into VWM to improve memory performance (Wang et al., 2016). More specifically, it was found that memory performance for multiple (to-be-memorised) features was superior when connecting to fewer spatial locations. That is, when two features occupied one location the memory performance was better than when they occupied two locations (i.e., each their own). Wang and colleagues (2016) thus argued that binding other features with task-irrelevant spatial information would strengthen the memory representation suggesting that it is possible to bind different types of features into an integrated unit.

Fundamental to this idea of binding is that the spatial information of an object plays an important role in VWM storage as it anchors visual features to a specific location (Baddeley & Hitch, 1974). Moreover, anchoring visual features through locations occurs regardless of whether the location is relevant (Foster et al., 2017; Rajsic et al., 2017; Schneegans & Bays, 2017; but see Udale et al., 2017, 2018). Consistent with this notion, spatial information has also been shown to act as a powerful cue for retrieving other memorised visual information (Dell'Acqua et al., 2010; Richardson & Spivey, 2000; Spivey & Geng, 2001; Theeuwes et al., 2011).

While it appears clear that irrelevant spatial information can be readily bound to task-relevant non-spatial features, this may not come as a surprise given the special status spatial information enjoys in the visual system. In the present study, we sought to answer the question whether automatic binding of features is a general phenomenon that is not restricted to spatial information alone. In other words, the present study investigated whether automatic binding also occurs when non-spatial features act as binding cues. To this end, we used three distinct features as binding cues in three experiments (i.e., colour in Experiment 1, spatial frequency in Experiment 2, and shape in Experiment 3). Key to the experimental design were two conditions: in the *informative* condition, two to-be-memorised features from different feature dimensions shared the same binding cue; while in the *non-informative* condition, each of the to-be-memorised features had its own binding cue. In the non-informative condition, the binding cue was therefore another feature that belonged to the same objects as the to-be-memorised features. Note that the feature acting as binding cue was completely task-irrelevant throughout every experiment. In other words, participants were neither required to memorise it, nor was using it necessary to be able to perform the task. If observers automatically bind task-relevant and irrelevant features into VWM through the use of a binding cue of *any* type of feature (i.e., not just spatial information), memory performance should be better in the informative relative to the non-informative condition in each of the three experiments. To foreshadow the results, VWM performance was higher in the informative condition than in the non-informative condition, supporting the automatic binding between task-relevant feature and task-irrelevant binding cue. In Experiment 4, we ruled out the possible impact from an imbalance in the number of task-irrelevant feature values between the conditions.

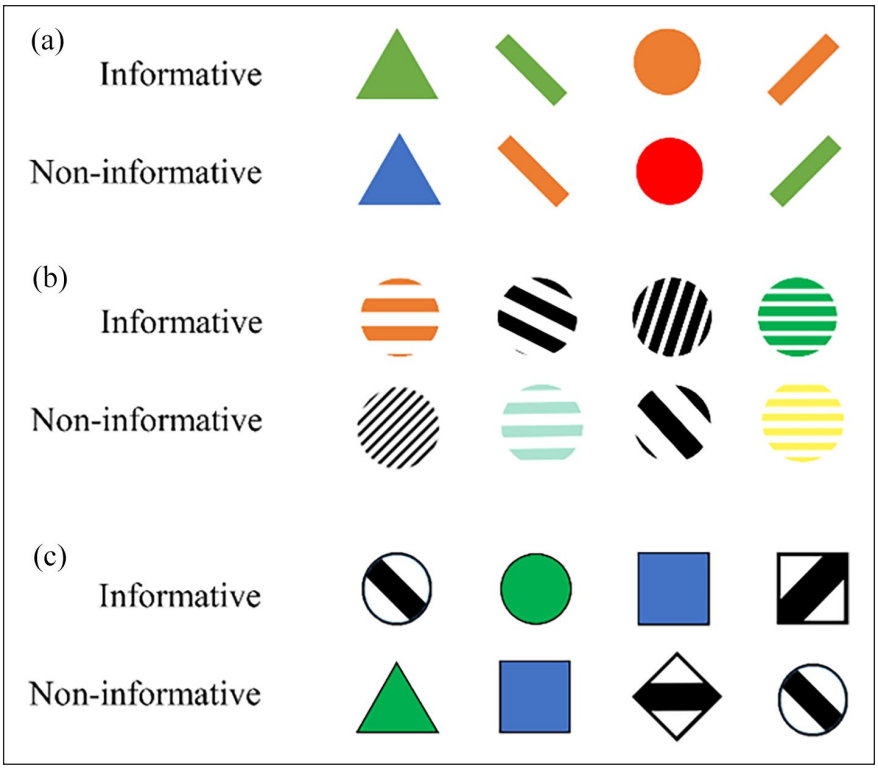


Figure 1. Examples of to-be-memorised objects in (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3.

Experiment 1: colour as a binding cue

Experiment 1 was designed to test whether observers employ colour as a binding cue to automatically bind to-be-memorised features with the binding cue together. In the informative condition, two to-be-memorised features from different dimensions (shape and orientation) shared the same colour, while all to-be-memorised features in the non-informative condition had different colours (see Figure 1a). If observers employ colour as a binding cue, memory performance should be better in the informative condition than in the non-informative condition. Note that the memory stimuli were presented sequentially to avoid any possible binding to the spatial location (Treisman & Zhang, 2006; Wang et al., 2016).

Method

The study procedure was approved by the Scientific and Ethical Review Committee of the Department of Psychology of the Zhejiang Normal University. Written informed consent was obtained from all the participants prior to the start of the study.

Participants. Twenty adults (16 females; mean age of 18.8 years) were recruited from students of the Zhejiang Normal University and received monetary compensation for their participation. All participants reported normal colour vision, and normal or corrected-to-normal visual acuity. Sample size was predetermined based on Wang et al., 2016, in which they observed a location-based binding effect with a relatively large effect size, partial $\eta^2 = .9$, suggesting that eight participants would be enough to replicate their critical finding with a power of 0.8. However, we did not exactly replicate their study and instead tested other non-spatial features. Thus, we significantly increased the number of participants from 8 to 20, to secure the power for the critical effect.

Apparatus and stimuli. The stimuli were presented against a grey background (Red-Green-Blue [RGB]: 128, 128, 128; 17.1 cd/m^2) on a 17-inch CRT monitor in a dimly lit laboratory room. The viewing distance was controlled using a chinrest at 71 cm distance. Stimulus presentation and response registration were controlled by customised scripts written in Python (www.python.org).

Two coloured shapes (circle, diamond, triangle, and square; subtended by 2° × 2°) and two coloured line segments (with their orientation ranging from 45° to 180°, in 45° steps; subtended by 0.5° × 2.5°) were used as memory stimuli (see Figure 1a). Their colours were randomly selected from a set of four different colours: red (RGB: 255, 0, 0), blue (RGB: 0, 0, 255), green (RGB: 0, 255, 0), and yellow (RGB: 255, 255, 0). In the non-informative condition, each stimulus had a unique colour. However, in the informative condition, one shape and one orientation

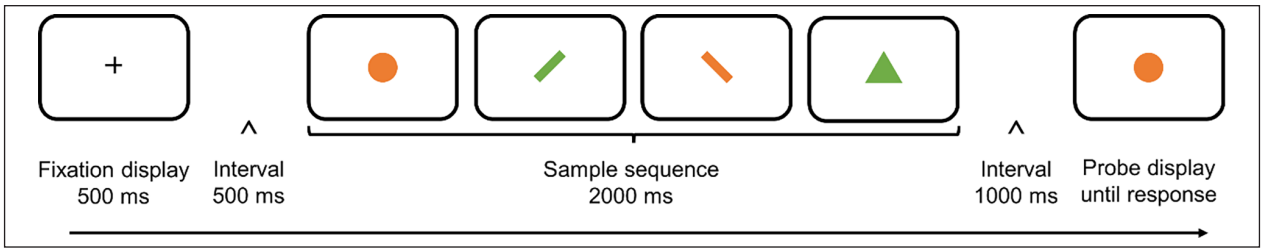


Figure 2. The sequence of events of a single trial exemplified on a trial from the informative condition. The inter-stimulus interval between each of the individual sample displays in the sample sequence was 200 ms.

shared the same colour, while—similarly—the other shape and the other orientation shared another colour.

Procedure and design. Figure 2 illustrates the sequence of events of a single trial, which was identical for each of the three experiments. Each trial began with the presentation of a fixation cross for 500 ms followed by an interval of 500 ms. Then, four to-be-memorised objects were presented sequentially and in random order at the centre of the display, avoiding any impact from the location information of to-be-memorised objects. This sequence of sample displays is referred to as sample sequence. Each sample display (i.e., sample object) was presented for 300 ms and followed by an inter-stimulus interval (ISI) of 200 ms. Participants were asked to memorise the orientations and shapes only and to ignore the colour (task-irrelevant feature). The total duration of the sample sequence was 2,000 ms, followed by an interval of 1,000 ms. Finally, a probe display was presented until participants responded. The next trial started after a randomly chosen inter-trial interval (ITI), ranging from 350 to 550 ms. Only a single object was presented in the probe display and participants were asked to indicate whether its orientation or shape had been shown in the sample sequence by pressing the "z" (indicating "yes") or "/" (indicating "no") key on a standard QWERTY keyboard. In half of the trials, the probe object was rendered in either an orientation or a shape that had not been shown in the sample sequence of that trial, but with one of the old task-irrelevant features (colours). On the other half of the trials, either the orientation or shape had been shown in the sample sequence of that trial with the same task-irrelevant feature (colour).

For the present experiment, a 2 (Cue type: informative vs. non-informative) × 2 (Probe type: shape vs. orientation) within-subject design was adopted. A critical design feature of this task is that participants were neither asked to nor was it necessary for them to memorise the colour of any of the objects to perform the task. Their task was to simply focus on memorising the orientation and shape of the sample objects. In other words, colour was a completely task-irrelevant feature. The experiment started with 20 practice trials followed by 2 blocks of 160 trials each. Conditions were tested in a blocked fashion and the order of blocks was counterbalanced across participants. Within each block, half of the trials contained a shape probe and the other half of the trials contained an orientation probe.

Analysis. Memory capacity k was calculated to serve as dependent variable using the formula provided by Cowan (2001):

$$k = S \times (H - F)$$

where S is the number of the to-be-memorised features, H is the hit rate, and F is the false alarm rate.

Results

Mean memory capacities (k) for the different cue types and probe types are shown in Figure 3a. A repeated-measures analysis of variance (ANOVA) with variables *cue type* (informative vs. non-informative) and *probe type* (orientation vs. shape) on mean memory capacity showed a significant main effect of cue type, $F(1, 19)=8.50$, $p=.009$, partial $\eta^2=.79$, and probe type, $F(1, 19)=5.85$, $p=.026$, partial $\eta^2=.63$. The two-way interaction was not statistically reliable, $F(1, 19)=0.53$, $p=.475$, partial $\eta^2=.11$. Mean capacity was higher for orientation ($M=0.85$, $SD=0.51$) than for shape probes ($M=0.73$, $SD=0.54$). More importantly, though, mean capacity was higher for the informative condition ($M=0.86$, $SD=0.52$) than for the non-informative condition ($M=0.72$, $SD=0.53$). Note that, in all experiments, the results pattern was the same when raw accuracy instead of k was used as the dependent variable. Mean hit rates and false alarm rates for experiments are presented in Table S1 (online Supplementary Material).

Discussion

The results of Experiment 1 showed a significant improvement in memory performance for both memorised features (i.e., orientation and shape) when they shared a task-irrelevant feature relative to when they did not share a task-irrelevant feature. We interpret this as evidence for a task-irrelevant feature (here colour) acting as a binding cue with which participants are able to anchor other, task-relevant, features. On

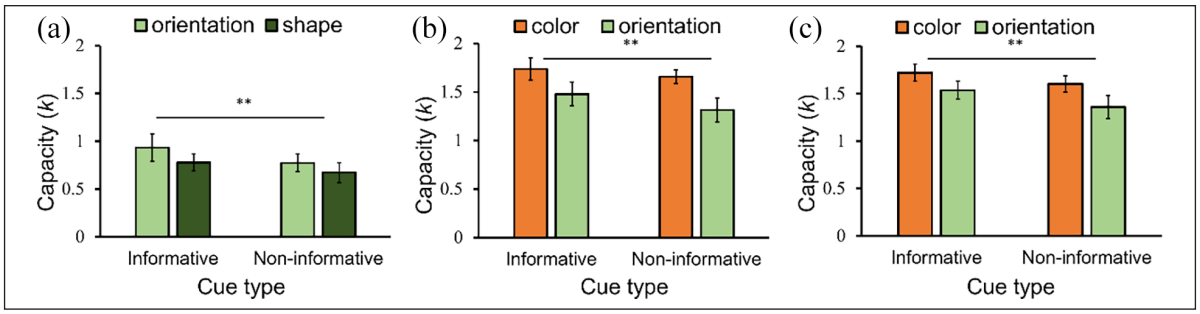


Figure 3. The results in (a) Experiment 1, (b) Experiment 2, and (c) Experiment 3.
Error bars denote the 95% within-subjects confidence intervals.

a broader scale, this provides evidence that not only spatial information as a feature of a to-be-memorised object (as shown in Wang et al., 2016), but also other, non-spatial, features can function as binding cues to automatically bind information together to improve memory performance.

In Experiments 2 and 3, we continue to explore whether evidence for the automatic binding generalises beyond the feature of space and colour by using spatial frequency in Experiment 2 and shape in Experiment 3 as binding cues.

Experiment 2: spatial frequency as a binding cue

Method

Twenty adults (17 females; mean age of 19.9 years) took part in Experiment 2. We adopted the same procedure, design, and analysis approach as in Experiment 1, but with different to-be-memorised features and a different binding cue. As illustrated in Figure 1b, four different gratings (subtended by 2° × 2°) were used as sample and probe objects, each possible to vary in colour, orientation, or spatial frequency. Colour and orientation were used as to-be-memorised features, whereas spatial frequency was used as the binding cue. Colours and orientations were randomly chosen from the same colour and orientation sets as in Experiment 1, whereas the spatial frequencies were randomly chosen from the frequency set: 0.7, 1.2, 2.2, and 4.2 deg/circle.

Importantly, and analogous to Experiment 1, the gratings containing colour information had the same orientation (180°), whereas the gratings containing orientation information had the same colour (black; RGB: 0, 0, 0). In the non-informative condition, the four to-be-memorised objects were all gratings with different spatial frequencies. In the informative condition, one grating containing colour information and one grating containing orientation information shared the same spatial frequency, while the other two gratings shared another spatial frequency. The present experiment therefore used a 2 (Cue type: informative vs. non-informative) × 2 (Probe type: colour vs. orientation) within-subject design.

Results

Mean memory capacities (k) for different cue types and probe types are shown in Figure 3b. A repeated-measures ANOVA with variables *cue type* (informative vs. non-informative) and *probe type* (orientation vs. colour) on mean memory capacity showed a significant main effect for cue type, $F(1, 19)=8.14$, $p=.01$, partial $\eta^2=.30$, and probe type, $F(1, 19)=27.81$, $p<.001$, partial $\eta^2=.55$. The two-way interaction was not statistically reliable, $F(1, 19)=0.16$, $p=.21$, partial $\eta^2=.08$. Mean memory capacity was higher for colour ($M=1.70$, $SD=0.21$) than that for orientation ($M=1.40$, $SD=0.40$). As it was the case in Experiment 1, mean memory capacity was higher for the informative condition ($M=1.61$, $SD=0.28$) than for the non-informative condition ($M=1.49$, $SD=0.33$).

Experiment 3: shape as the binding cue

Method

We recruited 20 participants in advance, but 2 of them quit the experiment during testing due to undisclosed personal reasons, leaving data of only 18 adults (17 females; with a mean age of 19.9) for analysis. We adopted the same procedure, design, and analysis approach as in Experiments 1 and 2, but with different to-be-memorised features and a different binding cue. As illustrated in Figure 1c, four different outline shape stimuli (subtended by 2° × 2°) were used as sample and probe objects each possible to vary in the colour and orientation inside the outline shape of the stimuli. Colour and orientation were used as to-be-memorised features, whereas the shape was used as the binding cue. The shapes, colours, and orientations were randomly chosen from the same shape, colour, and orientation sets as in Experiment 1.

Importantly, and analogous to Experiments 1 and 2, the shape stimuli containing orientation information were always of the same colour (black, RGB: 0, 0, 0). In the non-informative condition, the four to-be-memorised shape stimuli had different shapes. However, in the informative

condition, one colour and one orientation shared the same shape, while the other colour and orientation were presented inside another shape. For the present experiment, a 2 (Cue type: informative vs. non-informative) × 2 (Probe type: colour vs. orientation) within-subject design was adopted.

Results

Mean memory capacities (k) for different cue types and probe types are shown in Figure 3c. A repeated-measures ANOVA with variables *cue type* (informative vs. non-informative) and *probe type* (orientation vs. colour) on mean memory capacity showed a significant main effect for cue type, $F(1, 17) = 28.48$, $p < .00$, partial $\eta^2 = .63$, and probe type, $F(1, 17) = 12.88$, $p < .00$, partial $\eta^2 = .43$. The two-way interaction was not statistically reliable, $F(1, 17) = 0.77$, $p = .39$, partial $\eta^2 = .04$. Mean memory capacity was higher for colour ($M = 1.66$, $SD = 0.27$) than for orientation probes ($M = 1.45$, $SD = 0.40$). As it was the case for all prior experiments, mean memory capacity was higher for the informative condition ($M = 1.63$, $SD = 0.31$) than the non-informative condition ($M = 1.49$, $SD = 0.33$).

Experiment 4

In first three experiments, we found a consistent improvement of VWM performance for task-relevant features when they shared an additional, yet task-irrelevant feature. However, one might argue that the current results were driven by an imbalance in the number of task-irrelevant feature values in the informative (two values) relative to the non-informative (four values) condition. That is, memory performance in the informative condition may have been less affected due to a smaller number of task-irrelevant feature values that could interfere with the memory process. Although previous studies showed that processing of task-irrelevant features costs very few if any extra (attentional) resources in VWM (e.g., Gao et al., 2009; Marshall & Bays, 2013; Xu, 2010), Experiment 4 was designed to rule out this potential confounding factor for the present experiments. To this end, we replicated Experiment 1 but included an additional condition (i.e., the no-cue condition) in which all the stimuli were black. If the number of task-irrelevant feature values matters, there should be better memory performance in the no-cue relative to the other conditions, as the number of task-irrelevant feature values is the smallest one (i.e., colour was kept constant) in the no-cue condition. However, if the number of task-irrelevant features does interfere with memory processes, performance in the no-cue condition should be statistically indistinguishable from the non-informative condition.

Furthermore, we also examined whether the memory performance was indeed improved through binding different types of features, rather than exploiting task-irrelevant feature (the binding cue) to disambiguate which of the task-relevant features is being tested. We therefore included catch trials (1/8 trials) to the informative condition during which the probe was black. If improved memory performance was due to binding different types of features resulting in more effective storage of features, performance should keep constant regardless of the probe colour. If not, performance improvements are likely to be the consequence of exploiting the task-irrelevant feature to disambiguate which of task-relevant features is being tested, as nothing was relevant to binding per se.

Method

Due to the COVID-19 pandemic, only 15 of the originally 20 planned participants (13 females; with a mean age of 21.5) were successfully recruited and exposed to the same procedure as in Experiment 1 before the lab was closed again. According to the power calculation based on Experiment 1, a sample size of 15 participants was sufficient to replicate the findings of Experiment 1, with a calculated power that was larger than 0.99. However, an additional condition, the no-cue condition, was introduced during which all memory stimuli as well as the probe were black. Also, as alluded above, to investigate whether the current results were due to binding of different types of features or exploiting the task-irrelevant feature to disambiguate which of task-relevant features is being tested, we included catch trials in the informative condition in which the probe was black. Specifically, the probe was black in 1/8 of the trials (i.e., 20 trials) of the informative condition. The test order of the three conditions was counterbalanced across participants.

Results

Mean memory capacities (k) for different conditions are shown in Figure 4a. A repeated-measures ANOVA over three conditions on mean memory capacity showed a significant main effect, $F(2, 14) = 7.35$, $p < .01$, partial $\eta^2 = .34$. Planned comparisons showed that mean memory capacity was higher for the informative condition ($M = 1.86$, $SD = 0.14$) than the non-informative condition ($M = 1.74$, $SD = 0.13$), $t = 3.74$, $p < .01$, Cohen's $d = 0.97$, and no-cue condition ($M = 1.77$, $SD = 0.18$), $t = 3.74$, $p < .01$, Cohen's $d = 0.87$, confirming the results shown in Experiments 1–3. There was no statistically difference between non-informative condition and no-cue condition, $t = 0.79$, $p = .444$, Cohen's $d = 0.2$, BF10 = 0.34, suggesting that the number of task-irrelevant feature values does not affect memory performance.

Mean memory capacities for different probe types and probe colours in the informative condition are shown in Figure 4b. A repeated-measures ANOVA with *probe colour* (colour vs. black) and *probe type* (orientation vs.

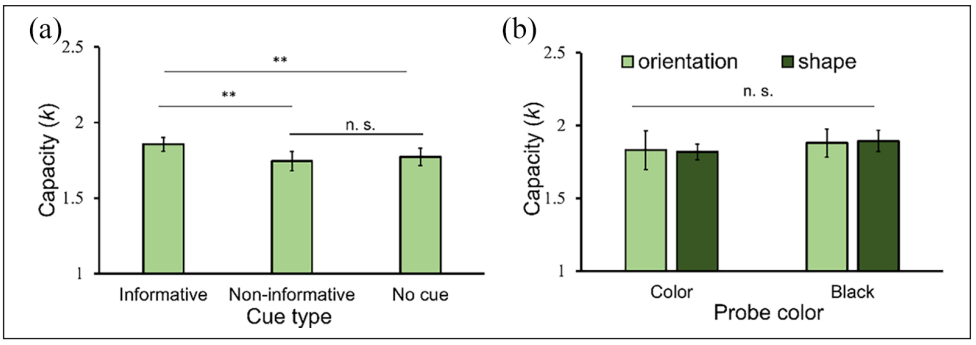


Figure 4. The results in Experiment 4: (a) mean memory capacity for different conditions and (b) mean memory capacity for different probe types and probe colours.
Error bars denote the 95% within-subjects confidence intervals.

colour) on mean memory capacity showed no significant main effects, nor interaction, all Fs < 3.14, all ps > 0.1, all BF10s < 0.81, suggesting that the increase in memory performance observed in the informative condition resulted from binding different types of features rather than an exploitation of the task-irrelevant feature so as to disambiguate which of task-relevant features is being tested.

General discussion

The current study demonstrates a consistent improvement of VWM performance for memorised features when they share an additional, yet task-irrelevant feature. This finding provides strong evidence for automatic binding as a general VWM mechanism: task-irrelevant features are used as binding cues to automatically bind task-relevant and irrelevant features together so as to improve memory performance. This is consistent with Wang et al. (2016) who showed that task-irrelevant spatial information is used as a binding cue to improve VWM performance. Importantly, though, we show that this automatic binding is not specific to spatial information, which is known to hold a prominent function in visual memory (e.g., Treisman & Gelade, 1980). Instead, automatic binding of features through the use of a binding cue occurs for many non-spatial, quite possibly any type of features in VWM.

Throughout the first three experiments, we found a consistent improvement of VWM performance when binding task-relevant and irrelevant features. However, it may be argued that these results were driven by an imbalance in the number of task-irrelevant feature values in the informative and non-informative conditions (two vs. four feature values). That is, as there was a smaller number of task-irrelevant feature values in the informative condition, memory performance may have been less strongly affected explaining the difference we found between conditions in these experiments. Experiment 4, however, showed that this is unlikely to be the root cause of the effect we observed. In this experiment, we showed that in a no-cue condition, in which all stimuli were coloured in black, memory performance was statistically indistinguishable from the non-informative condition in which each stimulus had its own colour. This finding is in line with a wealth of other studies that have suggested that processing of task-irrelevant features costs little to no extra (attentional) resources in VWM (Ecker et al., 2013; T. Gao et al., 2011; Z. F. Gao et al., 2009, 2010; Marshall & Bays, 2013; Xu, 2010; Yin et al., 2012).

In addition, Experiment 4 also provides converging evidence that memory improvement is due to binding different types of features resulting in more effective storage of features, rather than due to exploiting the task-irrelevant feature to disambiguate which of task-relevant features is being tested. Indeed, when including catch trials in the informative condition in which the probe was black, memory performance was statistically indistinguishable from trials with differing probe colours. This indicates that the binding is already formed during informative trials. Clearly, binding benefits remained observable even though the probe suddenly changed to black on catch trials. This suggests that the memory representation for the task-relevant features was strengthened already before memory was tested. It seems therefore apparent that such an improvement is due to the binding of a task-relevant to a task-irrelevant feature (i.e., binding cue).

It is interesting to note that previous studies which investigated feature binding in VWM found worse memory performance under conditions of feature binding. However, it is important to realise that these studies "forced" observers to bind different features together. For example, in Wheeler and Treisman's (2002) crucial feature-binding condition, to-be-memorised coloured objects either did or did not swap locations between the memory and test display and observers had to indicate whether a swap occurred. Under these circumstances, either memorising colour or location alone would make it impossible to knowingly give the correct response. In other words, observers were forced by the task demands to actively bind colour and location information together to able to do the task. As a result, memory performance in this feature-binding condition was

worse compared to when observers were required to memorise only a single feature. Our findings are therefore, to our knowledge, the first to show that observers can automatically bind different types of features together and thereby improve memory performance. We speculate that there might be different mechanisms underlying binding as occurred here and under forced conditions. When forced observers might attempt to actively exert top-down control to actively bind different features together. As this will require additional attentional resources, less resources are available for the actual memory process. As the features of the binding cue in our experiments were always task-irrelevant, observers may not have engaged in active exertion of top-down control which in turn did not occupy resources that made them unavailable for the memory process. The notion that processing of task-irrelevant features costs less or sometimes even almost no extra (attentional) resources is well-supported by a wealth of studies that have investigated how task-irrelevant features are stored in VWM (Ecker et al., 2013; T. Gao et al., 2011; Z. F. Gao et al., 2009, 2010; Marshall & Bays, 2013; Xu, 2010; Yin et al., 2012).

In conclusion, we argue that observers use task-irrelevant features as a binding cue to automatically bind task-relevant and irrelevant features to improve memory performance. This is not a process limited to spatial information but extends to any non-spatial feature.

Author contributions

C.Z. and X.L. equally contributed to the current study. C.Z., X.L., and B.W. designed the experiment; C.Z. collected and analysed the data; C.Z., X.L., M.F., and B.W. wrote the paper. All authors approved the final version of the manuscript for submission.

Declaration of conflicting interests

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ORCID iDs

Michel Failing https://orcid.org/0000-0001-5271-4951
Benchi Wang https://orcid.org/0000-0002-6348-9777

Data accessibility statement

Data can be accessed through https://github.com/wangbenchi/Shared_data, and none of the experiments was preregistered.

Supplementary material

The supplementary material is available at qjep.sagepub.com.

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