Effects of Spatial Orientation Information-Based Configuration on Visual Working Memory Performance: Postprint

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Date: 2018-09-07T00:00:00+00:00

Abstract

By examining the influence of two factors that constitute visual object configuration in visual working memory tasks, this study investigated the mechanism through which configuration affects visual working memory performance. Employing a change detection experimental paradigm, we systematically controlled variations in both the relative orientation of objects and the overall geometric form within configurations under two conditions: fixed configuration orientation and rotation, and examined their effects on visual working memory performance. The results demonstrated that, regardless of whether configuration orientation remained fixed or was rotated, working memory performance could be maintained at a high level as long as the relative orientation of objects was preserved, whereas geometric form exhibited no significant effect. These findings indicate that the relative orientation of objects in a configuration is the primary factor mediating the influence of configuration on visual working memory performance.

Full Text

Effect of Spatial Position Based Configuration on Visual Working Memory Performance

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Abstract

This study investigated the mechanism by which configuration influences visual working memory (VWM) performance by examining the effects of two configuration components in VWM tasks. Using a change detection paradigm, we systematically manipulated object relative position and overall geometric shape under both fixed and rotated configuration orientations to examine their impact on VWM performance. Results showed that VWM performance remained high as long as object relative position was preserved, regardless of whether configuration orientation remained fixed or was rotated, while geometric shape showed no significant effect. These findings suggest that object relative position is the primary factor through which configuration influences VWM performance.

Keywords: visual working memory; objects; configuration
Classification Code: B842

Visual working memory is a cognitive subsystem for the temporary storage and manipulation of information (Baddeley, 2012; Luck & Vogel, 2013) and represents a major research area in cognitive science. This system not only plays a crucial role in low-level cognitive processing (e.g., Hollingworth, Richard, & Luck, 2008) but is also closely related to various higher-level cognitive processes (e.g., Wickelgren, 1997), occupying a central position in the cognitive architecture. Due to its importance, researchers over the past decade have employed various techniques—including behavioral, neuroimaging, and computational modeling approaches—to effectively explore VWM mechanisms, including capacity (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997; Ma, Husain, & Bays, 2014; see reviews by Cowan, 2015; Oberauer, Farrell, Jarrold, & Lewandowsky, 2016; Shan & Li, 2010), representation precision (Zhang & Luck, 2008; Bays & Husain, 2008; Liu & Ku, 2017), storage format (Vogel, Woodman, & Luck, 2001; Wheeler & Treisman, 2002; Li, He, & Guo, 2015; see review by Christophel, Klink, Spitzer, Roelfsema, & Haynes, 2017), and interactions between working memory and other systems (Gao, Gao, Li, Sun, & Shen, 2011; Oberauer, Awh, & Sutterer, 2017).

Numerous studies have demonstrated that limited capacity is the most central characteristic of VWM, which can store only 3–4 simple objects (Luck & Vogel, 1997). The processing mechanisms for independent objects in VWM have been thoroughly explored in the aforementioned research. However, objects in the real world are often not independent but rather connected in various ways. Configuration represents crucial information for establishing such connections among objects. Configuration refers to the overall spatial distribution of multiple objects, reflecting their organizational pattern in space. Configuration information is relatively independent of absolute position and size; for example, similar triangles in geometry can be considered the same configuration.

The influence of configuration on memory performance has been supported by numerous studies. In Chun and Jiang' s (1998) research, visual scenes with repeatedly presented configurations were compared with randomly generated configurations in a visual search task, revealing higher memory performance in the repeated configuration condition. Further studies have shown that observers can store relational information among items based on their spatial configuration (Gmeindl, Nelson, Wiggin, & Reuter-Lorenz, 2011; Jiang, Chun, & Olson, 2004; Jiang, Olson, & Chun, 2000; Olson & Marshuetz, 2005; Woodman, Vecera,

& Luck, 2003). In these studies, participants completed a series of change detection tasks where multiple objects with spatial configuration information were initially presented, and participants were required to remember a particular dimension (e.g., color) before reporting whether it had changed in the subsequent test phase. When spatial configuration information changed, memory performance decreased significantly even when the configuration was task-irrelevant (e.g., when only color or shape needed to be remembered; see Jiang et al., 2000). Notably, this configuration effect persisted even when participants were explicitly instructed to ignore configuration information, suggesting that configuration processing may be mandatory and automatic (Jiang et al., 2000; Jiang et al., 2004). Developmental research has found that although older adults show decreased working memory capacity, their performance does not significantly differ from younger adults when configuration information is available (Olson, Zhang, Mitchell, Johnson, Bloise, & Higgins, 2004), indicating that configuration information can compensate for age-related working memory decline. Additionally, neuroimaging evidence supports the role of configuration in enhancing working memory performance: Xu and Chun (2007) found that even when configuration was task-irrelevant, participants could use it to organize memory information, as evidenced by lower inferior intraparietal sulcus (IPS) activity in configuration conditions (where three objects could be organized into a higher-level object) compared to non-configuration conditions (three independent objects).

Some researchers have examined configuration effects on VWM in dynamic scenes. For example, Hollingworth and Rasmussen (2010) demonstrated that memory performance remained high as long as the test configuration matched the preview configuration, even when object identities were swapped during motion, and this effect was unaffected by size scaling or position translation. Other studies have explored configuration mechanisms during dynamic changes, such as Sun et al. (2015), who found that configuration information remained effective when objects maintained consistent projective properties during motion, and Zhao et al. (2014), who showed that people tend to integrate tracked objects according to configuration for more efficient processing in multiple object tracking tasks.

Although these studies employed different task types, all demonstrated that storing and utilizing configuration information can enhance VWM performance. From an information theory perspective, if information to be encoded contains redundancy, capacity-limited cognitive systems must employ compression mechanisms to accommodate as much information as possible (Cover & Thomas, 1991). Based on this theory, we propose that the essence of configuration' s enhancement of working memory lies in its ability to effectively compress required information representations, enabling capacity-limited working memory systems to process more information. However, the specific mechanisms through which configuration improves information processing efficiency—or the precise ways configuration enhances memory performance—remain unclear. Previous studies using dynamic configurations involved objects in continuous motion (Sun et al., 2015; Zhao et al., 2014), which is meaningful for investigating configuration attributes closely related to dynamic changes. In contrast, research on static configurations allows for more precise control over different configuration forms to reveal more stable configuration characteristics. Previous static configuration studies primarily controlled changes in other attributes (absolute position, size, etc.), showing these factors were not essential for configuration effects. Instead, the determining factor was the composition of the configuration itself, which is determined by the spatial relationships among constituent objects (e.g., Hollingworth & Rasmussen, 2010).

We propose that the spatial relationships comprising configuration can be further subdivided into two aspects (Figure [Figure 1: see original paper]): (1) **Object relative position**—the position of each object relative to others within the configuration, such as upper-left or lower-right positions. Relative position remains constant during local displacement but changes when the configuration rotates (e.g., an object originally in the upper-left position moves to the lower-left after 90° counterclockwise rotation). (2) **Overall geometric shape**—the spatial shape formed by object positions, which necessarily changes when objects are displaced but remains unchanged during configuration rotation. When both aspects are determined, a specific configuration can be uniquely identified. Understanding how each factor contributes to configuration' s influence on working memory would reveal the manner and basis of configuration' s effects.

To investigate the respective roles of these factors, we separated and manipulated relative position and geometric shape in configurations such that only one factor changed at a time, then examined working memory performance under these conditions. If relative position is the primary determinant of configuration, stored information from the preview phase can be effectively utilized and memory performance will be higher as long as relative position remains consistent with the preview. If geometric shape plays the primary role, memory performance should improve when geometric shape remains constant. We addressed these questions through three experiments.

Experiment 1

Experiment 1 examined the role of position information in enhancing VWM performance using a change detection paradigm. Participants reported whether object colors in the test phase differed from those in the preview phase. Two independent variables were manipulated: (1) whether the spatial positions of colored objects changed, and (2) whether the geometric shape of the object configuration changed.

Half of the trials were "color-unchanged" conditions where no new colors appeared in the test phase, while the other half were "new-color" conditions where an unpreviewed new color appeared. Since new colors had no corresponding relationship with the previewed configuration, data from new-color conditions were not suitable for revealing configuration mechanisms. Therefore, we analyzed only color-unchanged condition data, using discriminability (d) and reaction time as dependent variables, consistent with previous research (Hollingworth & Rasmussen, 2010; Mitroff, Scholl, & Wynn, 2004).

To ensure stimulus consistency, all 80 configuration forms used in the experiment were generated by a computer program following specific rules: Each configuration comprised four objects located in the first, second, third, and fourth quadrants relative to the screen center. The angle between each object-center line and the origin was defined as the positioning angle, with 0° pointing horizontally rightward. Baseline angles of 45°, 135°, 225°, and 315° were used, with positioning angles randomly selected within ±15° of these baselines to ensure objects fell within distinct quadrants. The distance from object centers to the origin ranged randomly between 2.5° and 3.5° of visual angle. To ensure discriminability between configurations, the average difference in positioning angles for objects in corresponding quadrants exceeded 4°, and the average distance difference exceeded 0.5° of visual angle across any two configuration pairs. Configuration settings are illustrated in Figure [Figure 2: see original paper].

Participants

Eighteen Zhejiang University students (11 male, 7 female) aged 18–24 participated. All had normal or corrected-to-normal vision. Participants provided informed consent and received course credit or 30 RMB as compensation.

Materials

Memory objects were 0.5° × 0.5° circles presented in six colors: red [255 0 0], yellow [255 255 0], purple [255 0 255], green [0 255 0], cyan [0 255 255], and blue [0 0 255]. Colors filled the central portion of circles with black edges. To suppress verbal processing, a concurrent articulatory task presented black Arabic digits (1–9) in 1° × 1° size for participants to silently rehearse.

Apparatus

The experiment was programmed using Matlab with the PsychToolbox package (Brainard, 1997) and run on a 32-bit Windows 7 computer. Stimuli were displayed on a 19-inch CRT monitor with 1024 × 768 resolution and 100 Hz refresh rate in a quiet, darkened room.

Procedure

The trial procedure is shown in Figure [Figure 3: see original paper]. Each trial began with two random digits presented centrally for 500 ms, which participants silently rehearsed throughout the trial to suppress verbal encoding of colors (e.g., Vogel et al., 2001). After digit offset, a fixation point appeared for 1000 ms, followed by a 4-object configuration with colored objects presented for 500 ms, then a 1500 ms blank interval.

After the blank interval, four objects reappeared. The configuration could be identical to the preview phase (original form) or a different configuration (new form). Colors could appear in the same quadrants as the preview phase (position-unchanged) or different quadrants (position-changed), creating four conditions (Figure [Figure 4: see original paper]): (a) original form–position unchanged; (b) new form–position unchanged; (c) original form–position changed; (d) new form–position changed. In position-changed conditions, no color appeared in its original location to control for stimulus physical change magnitude. Position changes involved either 90° clockwise or counterclockwise rotation (original quadrants 1,2,3,4 became 2,3,4,1 or 4,1,2,3) or diagonal swapping (1,2,3,4 became 3,4,1,2). Pilot studies showed equivalent performance across these transformation types without inducing strategic responding.

After probe presentation, participants had 2000 ms to respond whether a new color had appeared, with response accuracy and latency recorded. Following the color task, a digit appeared centrally, and participants reported whether it matched one of the rehearsal digits. An inter-trial interval of 1000–1500 ms preceded the next trial. Both tasks emphasized speed while maintaining accuracy.

Participants completed practice trials before the 240-trial formal experiment, with 60 trials per condition in random order. The experiment lasted approximately 45 minutes, with breaks every 40 trials.

Results and Discussion

To avoid response bias effects, accuracy data were converted to discriminability indices (d) using signal detection theory. Two-way repeated-measures ANOVAs (position factor × geometric shape factor) were conducted on d and reaction time data, with results shown in Figure [Figure 5: see original paper].

The position factor showed a significant main effect on discriminability: d was significantly higher in position-unchanged conditions (1.99) than in position-changed conditions (1.78), $F(1, 17) = 14.34$, $p < 0.01$, $\text{p}^2 = 0.46$. The geometric shape factor showed no significant main effect: d did not differ significantly between original-form (1.91) and new-form conditions (1.87), $F(1, 17) = 1.16$, $p = 0.30$. The position × shape interaction was also non-significant, $F(1, 17) = 0.13$, $p = 0.72$.

For reaction time, the position factor again showed a significant main effect, $F(1, 17) = 17.91$, $p < 0.01$, $\text{p}^2 = 0.51$, with shorter RTs in position-unchanged conditions (816 ms) than position-changed conditions (882 ms). The geometric shape factor was non-significant, $F(1, 17) = 2.00$, $p = 0.18$, with no difference between original-form (843 ms) and new-form conditions (855 ms). The position × shape interaction was non-significant, $F(1, 17) = 0.03$, $p = 0.86$.

In the new-form-position unchanged condition, configuration geometric shape changed but colors appeared in the same quadrants as the preview phase, preserving relative position. Results showed equivalent performance to the original-form-position unchanged condition, with no significant differences in discriminability or reaction time, and both conditions outperformed the two position-changed conditions. In other words, when object positions within the configuration remained unchanged, task efficiency remained high regardless of geometric shape changes. The non-significant main effect of geometric shape and the non-significant interaction between shape and position suggest that shape variation is not a primary influencing factor.

In VWM processing of objects and their attributes, the binding relationship between attributes and objects is crucial. When attribute-object associations can be effectively maintained from preview to test phases, VWM performance improves in both speed and accuracy. For example, object file theory research shows higher performance when visual attributes and object identity remain constant during brief motion (Gordon, 2004; Gordon & Irwin, 1996; Mitroff, Scholl, & Noles, 2007; Mitroff et al., 2004). Other studies highlight the importance of the link between visual attributes and the spatial positions where objects appear (Hollingworth & Rasmussen, 2010; Zelinsky & Loschky, 2005).

From this perspective, Experiment 1 demonstrates that the link between object color and relative position plays a vital role in improving task performance. Critically, this relative position does not correspond to precise spatial coordinates but rather approximate positions relative to the configuration, which can vary within a certain range while preserving position identity. This invariance appears to be a more fundamental factor in enhancing VWM performance.

However, Experiment 1 did not include a condition where visual features remained consistent with geometric shape while inconsistent with relative position, preventing direct comparison of the two factors' roles. Further experiments were needed to explore this issue.

Experiment 2

Experiment 1 controlled color presentation position and showed that memory performance remained high when spatial geometric configuration changed but color feature positions remained consistent with the preview phase, suggesting that position information is an effective factor for enhancing VWM performance. However, Experiment 1's new-form condition used different configuration shapes from the preview phase and did not include a condition where geometric shape remained constant while position changed, preventing examination of performance when only geometric shape was preserved.

Since geometric shape remains constant during rotation, we manipulated configuration through rotation to examine geometric shape' s role. Based on this rationale, Experiment 2 included three conditions: original form-position unchanged, configuration rotation-position unchanged, and configuration rotation-geometric consistent. Dependent variables were recorded as in Experiment 1. In the configuration rotation-geometric consistent condition, the quadrants where visual features appeared also changed according to the rotation direction, meaning visual features remained consistent with the geometric shape. If performance in this condition remained low, it would suggest geometric shape has no significant effect; conversely, if performance remained high, it would indicate geometric shape is also an important configuration factor.

Participants

Eighteen Zhejiang University students (8 male, 10 female) aged 19-23 participated. All had normal or corrected-to-normal vision and had not participated in Experiment 1. Participants provided informed consent and received compensation.

Design and Procedure

Experiment 2' s basic design followed Experiment 1 with three conditions: original form-position unchanged, configuration rotation-position unchanged, and configuration rotation-geometric consistent (Figure [Figure 6: see original paper]). The original form-position changed condition from Experiment 1 was omitted because it had already been examined and was not the primary focus; retaining the original form-position unchanged condition as a baseline was sufficient.

During configuration rotation, colors in the test phase could appear in their original quadrants (configuration rotation-position unchanged) or change consistently with the rotated geometric shape (configuration rotation-geometric consistent). Rotation was either 90° clockwise or counterclockwise (counterclockwise shown in Figure [Figure 6: see original paper]), ensuring objects remained in four quadrants and maintaining consistent transformation magnitude across trials.

Results and Discussion

One-way repeated-measures ANOVA on Experiment 2 data revealed significant differences among the three conditions (Figure [Figure 7: see original paper]). For discriminability, the main effect was significant, $F(2, 34) = 8.45$, $p < 0.01$, $p^2 = 0.33$. Follow-up comparisons showed no significant difference between configuration rotation-position unchanged (2.03) and the original form-position unchanged baseline (2.12), $F(1, 17) = 0.90$, $p = 0.36$, but a significant difference between configuration rotation-geometric consistent (1.78) and baseline, $F(1, 17) = 13.05$, $p < 0.01$, $p^2 = 0.43$.

Reaction time data mirrored discriminability results, with a significant main effect across conditions, $F(2, 34) = 3.81$, $p < 0.05$, $p^2 = 0.18$. Comparisons revealed no significant difference between configuration rotation-position unchanged (867 ms) and baseline (856 ms), $F(1, 17) = 0.45$, $p = 0.51$, but a significant difference between configuration rotation-geometric consistent (896 ms) and baseline, $F(1, 17) = 6.83$, $p < 0.05$, $p^2 = 0.29$.

Experiment 2 replicated Experiment 1' s pattern: when position remained unchanged, performance stayed high regardless of whether the configuration' s geometric shape was rotated. Performance was lower in the configuration rotation–geometric consistent condition. When configuration rotated, maintaining color positions consistent with the preview phase necessarily disrupted consistency between color position and geometric shape. In the configuration rotation–geometric consistent condition, consistency between color position and geometric shape was preserved while relative position changed due to rotation. Thus, these two conditions independently preserved either relative position or geometric shape consistency. The position-consistent condition performed at baseline level and significantly outperformed the geometric shape-consistent condition, suggesting task performance primarily depends on relative position rather than geometric shape.

Experiment 3: Effects of Object Position and Geometric Shape with Visual Rotation Cues

Experiment 2 used rotated configurations where geometric shape remained constant, but this consistency did not show a significant influence like position did. The rotation in Experiment 2 presented only two discontinuous states (pre- and post-rotation), whereas mental rotation of visual representations is typically a continuous process. Experiment 3 provided visual rotation cues (Figure [Figure 8: see original paper]) to indicate the configuration rotation process, making it continuous. If geometric shape disruption impairs configuration effects, it would suggest geometric shape is also important for working memory, with its previous null effect due to the lack of a continuous process. Conversely, if preserving only object relative position consistency maintains configuration effects, it would indicate VWM task performance is not influenced by geometric factors.

Accordingly, Experiment 3 included three conditions: configuration rotation-geometric consistent, new-form-position rotated, and new-form-position random change (Figure [Figure 9: see original paper]). In the new-form-position rotated condition, the test configuration was randomly selected from the configuration pool while object positions matched the rotation cue. In the new-form-position random change condition, the test configuration was randomly selected and all color positions differed from the preview, excluding cases consistent with the rotation cue. This differed from Experiment 1' s new-form-position changed condition.

Objectively, both configuration shape and object positions changed in the new-form-position random change condition, while both geometric shape and object positions matched the rotation cue in the configuration rotation-geometric consistent condition. In the new-form-position rotated condition, only object positions matched the rotation cue. Thus, the new-form-position random change condition served as a baseline for comparison. If only the configuration rotation-geometric consistent condition showed higher performance than baseline while the new-form-position rotated condition showed no advantage, it would indicate geometric shape is essential for utilizing configuration information under rotation. If both conditions showed equivalent performance advantages, it would indicate that position consistency alone is sufficient for configuration utilization.

Participants

Eighteen Zhejiang University students (9 male, 9 female) aged 19–25 participated. All had normal or corrected-to-normal vision and had not participated in previous experiments. Participants provided informed consent and received compensation.

Design and Procedure

Experiment 3' s procedure was identical to Experiment 2 with the addition of rotation cues (Figure [Figure 8: see original paper]). During the preview phase, a cue frame appeared centrally alongside the stimulus. After preview offset, the frame remained and began rotating after 250 ms, completing a 90° rotation in 1000 ms in the same direction as the test configuration, then remained stationary for 250 ms before the test phase. Memory retention time was 1500 ms, identical to Experiment 2. Since the frame was square with identical shape before and after rotation, it provided no additional visual cues beyond the rotation process.

Experiment 3 included three conditions: (1) configuration rotation-geometric consistent, (2) new-form-position rotated, and (3) new-form-position random change (Figure [Figure 9: see original paper]). The configuration rotation-geometric consistent condition matched Experiment 2, but Experiment 3 omitted the original form-position unchanged condition and added new-form-position rotated (object positions consistent with rotation cue) and new-form-position random change conditions. Both new-form conditions used newly sampled test configurations, with the new-form-position random change condition serving as baseline.

Results and Discussion

Data analysis followed previous experiments, with results shown in Figure [Figure 10: see original paper]. Main effects were significant for both discriminability (d) and reaction time: $F(2, 34) = 4.85$, $p < 0.05$, $p^2 = 0.22$, and $F(2, 34) = 8.16$, $p < 0.01$, $p^2 = 0.32$, respectively. Comparing the two primary conditions to baseline, configuration rotation-geometric consistent showed significantly higher performance, $F(1, 17) = 4.78$, $p < 0.05$, $p^2 = 0.22$, as did new-form-position rotated, $F(1, 17) = 13.05$, $p < 0.01$, $p^2 = 0.43$. Reaction time data were consistent: both configuration rotation-geometric consistent and new-form-position rotated conditions outperformed baseline, $F(1, 17) = 8.31$, $p < 0.05$, $p^2 = 0.33$, and $F(1, 17) = 10.95$, $p < 0.01$, $p^2 = 0.39$, respectively. No significant differences emerged between configuration rotation-geometric consistent and new-form-position rotated conditions for either discriminability or reaction time.

Compared to baseline, the configuration rotation-geometric consistent condition used test configurations derived strictly by rotating the preview configuration according to the cue, preserving consistency in both geometric shape and object positions with the rotation process, yielding significant performance advantages. In the new-form-position rotated condition, test configuration geometry was newly sampled and unrelated to the preview, with only object positions matching the rotation cue. Performance in this condition was equivalent to configuration rotation-geometric consistent and also showed advantages over baseline. In other words, superior performance did not require complete consistency between geometric shape and object positions with rotation; as long as test object positions transformed according to the rotation cue, performance advantages emerged even when configuration geometry differed from the preview.

Experiment 3' s results demonstrate that even after mental rotation operations on configurations, object position consistency remains the key factor in configuration' s influence on VWM performance. Since rotation cues only indicated rotation without directly presenting the rotated configuration, participants primarily relied on subjectively rotated representations. This suggests that even for configurations formed through subjective manipulation rather than direct visual input, locating a specific object depends primarily on its relative position.

Numerous studies have shown that configuration plays an important role in enhancing VWM performance. Previous research has demonstrated that configuration information can undergo translation or scaling from preview to test phases without manipulating geometric shape changes (e.g., Jiang et al., 2000; Hollingworth & Rasmussen, 2010). While this approach advanced understanding of configuration processing characteristics—such as independence from position and size (Jiang et al., 2000) and persistence despite object identity mismatches (Hollingworth & Rasmussen, 2010)—we argue that without varying geometric shape, the specific mechanisms of configuration' s effects cannot be thoroughly explored.

As previously described, configuration is the spatial distribution pattern of multiple objects. To understand the internal processing mechanisms of this pattern, an effective approach is to control influencing factors and examine the process from completely preserving the initial form to completely losing original features. During this process, different factors affecting configuration can reveal their roles, thereby elucidating the specific mechanisms through which configuration enhances working memory performance. Recent research has begun exploring configuration processing characteristics using dynamic changes (Sun et al., 2015; Zhao et al., 2014). However, real-world scenarios often require processing and utilizing a specific configuration, and which factors configuration depends on during this process requires exploration through factor manipulation.

Based on this rationale, we manipulated the two types of information contained in configurations—relative position and geometric shape—varying one while holding the other constant. If different information has different processing mechanisms, these differences would manifest under different transformation conditions. Results showed that memory performance was high when object relative position remained unchanged, but low when geometric shape remained constant while relative position changed. When configurations were subjectively rotated, relative position consistency continued to play the primary role.

General Discussion

Object-Attribute-Position Binding Relationships

Encoding specificity theory posits that retrieval is easier when contextual conditions at encoding and retrieval are similar (Tulving & Thomson, 1973). From this perspective, configuration can be viewed as the context for visual features —the closer the test configuration matches the preview configuration, the more beneficial for retrieving associated visual information. However, subsequent research has revealed more nuanced phenomena: similarity between preview and test is not merely superficial; similar facilitation effects are observed when intrinsic attributes have specific relationships, such as object identity consistency or configuration shape consistency (Hollingworth & Rasmussen, 2010; Kahneman, Treisman, & Gibbs, 1992).

These findings suggest that objects, visual attributes, and spatial positions have tight, complex binding relationships in visual cognition. Many studies have examined binding between visual attributes and objects, generally concluding that different visual attributes concentrated on a specific object can be integrated into an independent object representation (Treisman, 1996, 1998; Wheeler et al., 2002). Notable findings also exist regarding object-position binding, such as evidence that objects in VWM are primarily bound to relative rather than absolute positions (Hollingworth, 2007).

Building on previous research, the present study’ s main contribution is the discovery that object-position binding does not necessarily depend on exact positions within the visual context. As long as relative position is preserved, this binding can exist and function. Object-relative position binding implies that maintaining precise correspondence between objects and their visual context during translation or scaling allows VWM performance to remain high, while object-relative position connections enable high memory performance even when object positions within the visual context shift to some extent. This demonstrates the flexibility of the human visual cognitive system in handling visual tasks and its ability to adapt to input variations.

However, object relative position depends on relationships with reference objects. In a configuration, an object’ s relative position reference is other objects. If these objects shift substantially, relative position judgments may be affected. Therefore, position shifts must remain within a certain range to preserve relative position invariance. To control shift magnitude, we used rule-generated 4-object configurations ensuring position differences between configurations were not excessive, thereby maintaining a stable reference frame for relative position judgments. Our findings are based on this premise. An important question for future research is determining the extent to which object position shifts affect the existence and function of relative position.

Encoding Format of Object Configuration in Working Memory

The primary encoding unit of VWM is visual objects. Configuration, as a collection of multiple objects, also demonstrates important effects in working memory. Chun and Jiang' s (1998) research showed that configuration can be maintained in memory and exert effects during task completion. Other studies have treated configuration as an organizational method for object positions in working memory (Hollingworth, 2007; Olson et al., 2005). However, current research has inadequately explored how configuration is encoded in VWM.

If configuration is viewed as an organizational method for object position information, and considering previous findings that configuration is unaffected by translation or size changes, then defining geometric shape and orientation should precisely specify a configuration. However, our study found that when colors appeared on same-position objects, VWM performance remained high regardless of geometric shape changes. When position changed, tasks could still be completed without requiring precise geometric shape matching, but performance declined significantly when object position changed due to orientation rotation. This suggests that observers' memory encoding comprises two aspects: holistic encoding based on approximate relative position rather than geometric shape, and encoding of color features themselves. When holistic encoding can be utilized, higher response speed and discriminability are achieved. Conversely, when position is inconsistent with the encoding phase preventing holistic processing, stored feature codes must be scanned to detect new features, resulting in lower speed and discriminability.

Another finding is that when rotation cues enable mental rotation operations, performance can remain high if object position changes are consistent with the rotation, again without requiring geometric shape consistency. Research shows cognitive systems can mentally rotate visual representations (Cooper & Shepard, 1973; Metzler & Shepard, 1974; Shepard & Hurwitz, 1984; Shepard & Metzler, 1988). Configuration representations also exhibit this property, demonstrating mental rotation capability and showing similar characteristics to directly visually encoded configurations after rotation. However, this ability has limitations: configuration updating during rotation changes requires cues. Thus, configuration information in VWM has both flexibility and adaptability, but is also constrained by inherent cognitive processing methods.

Maintenance of Configuration Information in Working Memory

Like all information maintained in working memory, configuration information faces maintenance capacity limitations. This study found that with cues, configuration can be mentally rotated in working memory and function in its rotated state, yet the original pre-rotation state is not eliminated from working memory.

This suggests mental rotation operations do not completely update stored configurations. Even when new position information after rotation can be utilized, original position information continues influencing task completion, indicating that working memory can simultaneously maintain both pre- and post-rotation states.

Maintaining more information is generally beneficial for memory task efficiency. However, many VWM studies show a trade-off between stored information precision and quantity (Alvarez & Cavanagh, 2004; Wilken & Ma, 2004). The simultaneous maintenance of initial and rotated configuration states in our study did not appear to reduce configuration effects. This may be because two different orientations of the same configuration do not occupy double storage capacity but may share information codes. Alternatively, configuration storage may not have exceeded capacity limits.

Future research should further explore working memory capacity for configurations, the processing stages where configuration functions, and other factors that may influence configuration effects (attentional resources, memory load, etc.).

Conclusion

Through three experiments examining how different informational factors in configuration affect working memory performance, we conclude: (1) Object spatial relative position is the primary factor through which configuration influences VWM performance; (2) Overall geometric shape has no significant effect on VWM; (3) After mental rotation of configuration, relative position remains the dominant factor, consistent with conditions without rotation.

References

Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science, 15*(2), 106–111.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual review of psychology, 63*, 1-29.

Bays, P. M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science, 321*(5890), 851-854.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Christophel, T. B., Klink, P. C., Spitzer, B., Roelfsema, P. R., & Haynes, J. D. (2017). The distributed nature of working memory. *Trends in cognitive sciences, 21*(2), 111–124.

Chun, M. M., & Jiang, Y. H. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*(1), 28–71.

Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. In: Chase, W.G. (Ed.), *Visual Information Processing*. Academic Press, New York.

Cover, T. M., & Thomas, J. A. (1991). *Elements of information theory*. New York: Wiley.

Cowan, N. (2015). George Miller' s Magical Number of Immediate Memory in Retrospect: Observations on the Faltering Progression of Science. *Psychological Review, 122*(3), 536–541.

Gao, T., Gao, Z. F., Li, J. S., Sun, Z. Q., & Shen, M. W. (2011). The perceptual root of object-based storage: An interactive model of perception and visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 37*(6), 1803-1823.

Gmeindl, L., Nelson, J. K., Wiggin, T., & Reuter-Lorenz, P. A. (2011). Configural representations in spatial working memory: Modulation by perceptual segregation and voluntary attention. *Attention, Perception, & Psychophysics, 73*(7), 2130-2142.

Gordon, R. D. (2004). Attentional allocation during the perception of scenes. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 760–777.

Gordon, R. D., & Irwin, D. E. (1996). What' s in an object file? Evidence from priming studies. *Perception & Psychophysics, 58*(8), 1260–1277.

Hollingworth, A. (2007). Object-position binding in visual memory for natural scenes and object arrays. *Journal of Experimental Psychology: Human Perception and Performance, 33*(1), 31–47.

Hollingworth, A., Richard, A. M., & Luck, S. J. (2008). Understanding the function of visual short-term memory: Transsaccadic memory, object correspondence, and gaze correction. *Journal of Experimental Psychology: General, 137*(1), 163–181.

Hollingworth, A., & Rasmussen, I. P. (2010). Binding objects to locations: The relationship between object files and visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 36*(3), 543–564.

Jiang, Y. H., Chun, M. M., & Olson, I. R. (2004). Perceptual grouping in change detection. *Perception & Psychophysics, 66*(3), 446–453.

Jiang, Y., Olson, I. R., & Chun, M. M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*(3), 683-702.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology, 24*(2), 175–219.

Li C. H., He X., & Guo C. Y. (2015). The Storage Mechanism of Multi-feature Objects in Visual Working Memory. *Acta Psychologica Sinica, 47*(6), 734–745. [黎翠红, 何旭, 郭春彦. (2015). 多特征刺激在视觉工作记忆中的存储模式. 心理学报, 47(6), 734–745.]

Liu Z. Y., & Ku Y. X. (2017). Perceiving better, inhibiting better: Effects of perceptual precision on distractor-inhibition processes during working memory. *Acta Psychologica Sinica, 49*(10), 1247–1255. [刘志英, 库逸轩. (2017). 知觉表征精度对工作记忆中抑制干扰能力的影响. 心理学报, 49(10), 1247–1255.]

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281.

Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: From psychophysics and neurobiology to individual differences. *Trends in Cognitive Sciences, 17*(8), 391–400.

Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience, 17*(3), 347-356.

Metzler, J., & Shepard, R. N. (1974). Transformational studies of the internal representation of three-dimensional objects. In R. L. Solso (Ed.), *Theories in cognitive psychology: The Loyola Symposium.* Oxford, England: Lawrence Erlbaum.

Mitroff, S. R., Scholl, B. J., & Noles, N. S. (2007). Object files can be purely episodic. *Perception, 36*(12), 1730-1736.

Mitroff, S. R., Scholl, B. J., & Wynn, K. (2004). Divide and conquer how object files adapt when a persisting object splits into two. *Psychological Science, 15*(6), 420–425.

Oberauer, K., Awh, E., & Sutterer, D. W. (2017). The role of long-term memory in a test of visual working memory: Proactive facilitation but no proactive interference. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*(1), 1–22.

Oberauer, K., Farrell, S., Jarrold, C., & Lewandowsky, S. (2016). What limits working memory capacity? *Psychological Bulletin, 142*(7), 758-799.

Olson, I. R., & Marshuetz, C. (2005). Remembering "what" brings along "where" in visual working memory. *Attention, Perception, & Psychophysics, 67*(2), 185–194.

Olson, I. R., Zhang, J. X., Mitchell, K. J., Johnson, M. K., Bloise, S. M., & Higgins, J. A. (2004). Preserved spatial memory over brief intervals in older adults. *Psychology and Aging, 19*(2), 310–317.

Shan, X.J., & Li, S. X. (2010). The new development of mechanism of visual working memory capacity based on new models. *Advances in Psychological Science, 18*(11), 1684-1691. [单西娇, 李寿欣. (2010). 由两个模型看视觉工作记忆容量机制的研究. 心理科学进展, 18(11), 1684-1691.]

Shepard, R. N., & Hurwitz, S. (1984). Upward direction, mental rotation, and discrimination of left and right turns in maps. *Cognition, 18*(1-3), 161-193.

Shepard, S., & Metzler, D. (1988). Mental rotation: Effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance, 14*(1), 3-11.

Sun, Z. Q., Huang, Y., Yu, W. J., Zhang, M., Shui, R. D., & Gao, T. (2015). How to break the configuration of moving objects? Geometric invariance in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 41*(5), 1247-1259.

Treisman, A. (1996). The binding problem. *Current Opinion in Neurobiology, 6*(2), 171-178.

Treisman, A. (1998). Feature binding, attention and object perception. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 353*(1373), 1295-1306.

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review, 80*(5), 352-373.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 92-114.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*(1), 48-64.

Wickelgren, I. (1997). Getting a Grasp on Working Memory. *Science, 275*(5306), 1580-1582.

Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision, 4*(12), 1-11.

Woodman, G. F., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic bulletin & review, 10*(1), 80-87.

Xu, Y. D., & Chun, M. M. (2007). Visual grouping in human parietal cortex. *Proceedings of the national academy of sciences, 104*(47), 18766-18771.

Zelinsky, G. J., & Loschky, L. C. (2005). Eye movements serialize memory for objects in scenes. *Attention, Perception, & Psychophysics, 67*(4), 676-690.

Zhang, W. W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature, 453*(7192), 233-235.

Zhao, L., Gao, Q. Y., Ye, Y., Zhou, J. F., Shui, R. D., & Shen, M. (2014). The role of spatial configuration in multiple identity tracking. *PLoS ONE, 9*(4), e93835.

Note: Figure translations are in progress. See original paper for figures.