NATIONAL RESEARCH UNIVERSITY HIGHER SCHOOL OF ECONOMICS

As a manuscript

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The Structure of Visual Working Memory Units

Summary
for the purpose of obtaining academic degree
Doctor of Philosophy in Psychology

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The dissertation was prepared at the Laboratory for Cognitive Research, National Research University Higher School of Economics.

Three published articles were selected for the defense:

1. Markov, Y.A., Utochkin, I. S. (2022). Effects of item distinctiveness on the retrieval of objects and object-location bindings from visual working memory. Attention, Perception, & Psychophysics
2. Markov, Y.A., Utochkin, I. S., & Brady T. F. (2021). Real-world objects are not stored in holistic representations in visual working memory. Journal of Vision, 21(3): 18, 1–24. DOI: 10.1167/jov.21.3.18.
3. Markov, Y.A., Tiurina, N.A., & Utochkin, I.S. (2019). Different features are stored independently in visual working memory but mediated by object-based representations. Acta Psychologica, 197, 52-63. DOI: 10.1016/j.actpsy.2019.05.003

The results are also published in the following articles on this topic:

4. Markov, Y.M., Tiurina, N.A., Stakina, Y.M., & Utochkin, I.S. (2017). The capacity and precision of visual working memory for objects and ensembles. Psychology. Journal of HSE, 14(4), 735-756. DOI: 10.17323/1813-8918-2017-4-735-755

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1. Introduction

General research problem

At every second, we perceive and interact with the complex and rich world that contains various objects with many details. Working memory is a highly limited cognitive system (Cowan, 2001; Miller, 1956) that allows us to store and operate information about the perceived world immediately accessible for the ongoing task (Baddeley, 1986; Baddeley & Hitch, 1974). Visual working memory operates visual information and, as a subsystem of working memory, is also limited (Luck & Vogel, 1997). It is essential to understand the nature of the representations maintained by visual working memory to build a comprehensive theory of visual working memory. For the last several decades, there has been a long-lasting debate about the structural units of visual working memory. Numerous studies have provided evidence that both unitary objects (Cowan, Chen, & Rouder, 2004; Kahneman, Treisman, & Gibbs, 1992; Lee & Chun, 2001; Luck & Vogel, 1997; Luria & Vogel, 2011; Treisman, 1999; Vogel, Woodman, & Luck, 2001; Xu, 2002; Xu & Chun, 2006; Zhang & Luck, 2008) and separate features (see Brady, Konkle, & Alvarez, 2011, for review; Bays, Catalao, & Husain, 2009; Bays, Wu, & Husain, 2011; Fougnie & Alvarez, 2011; Fougnie, Cormiea, & Alvarez, 2013; Pertzov, Dong, Peich, & Husain, 2012; Shin & Ma, 2017; Wang, Cao, Theeuwes, Olivers, & Wang, 2017; Wheeler & Treisman, 2002) could be the units of visual working memory. How could different studies come to such different conclusions? What are the core units of visual working memory? Does visual working memory store whole objects representations or distinct features? Is it possible that neither objects, nor features but something more complex is a unit of visual working memory? Or does it depend on the task? How is information retrieved in various tasks from visual working memory? These are the central questions to the topic of the current work, which characterize the **problem of research**.

The **main aim** of this PhD thesis is to study the structure of visual working memory representations.

Research goals

- To analyze current research on the topic of visual working memory representations

- To empirically test feature- and object-based units of visual working memory
- To conduct base of images of real-world objects and test visual working memory for real-world objects
- To test retrieval from visual working memory under different tasks

Methodological and theoretical basis of the current work

The dissertation is based on several theoretical frameworks: feature-integration theory of visual perception and attention (Treisman, 2006); object-based visual working memory theories (Luck & Vogel, 1997; Zhang & Luck, 2008); resource-based models of visual working memory (Bays & Husain, 2008; Bays, Catalao & Husain, 2009; Bays, 2014; Bays, 2015; Schneegans & Bays, 2017); interference model of visual working memory (Oberauer & Lin, 2017); hierarchical encoding theory in visual memory (Brady, Konkle, Alvarez, 2011; Brady, Alvarez, 2011); target confusability competition model (Schurgin, Wixted, & Brady, 2020).

Methods of the research

Laboratory psychophysical experiments using methods modified for research tasks: continuous report task (Wilken & Ma, 2004; Zhang & Luck, 2008), exemplar-state task (Utochkin & Brady, 2020). We used descriptive statistics, RM ANOVA, t-tests to analyze the results. We used mixture models to process raw data (Zhang & Luck, 2008; Suchow, Brady, Fougnie, & Alvarez, 2013).

Summary of scientific novelty

- We showed that the recall of object features from working memory depends on within-, not cross-dimension load suggesting independent memory capacities for different features. Importantly, we also showed that this cross-dimensional independence is violated when different features are spatially separated and clearly belong to different objects, suggesting that object-based representations play the role of a mediator that decreases interference between the contents of visual working memory.
- We reported for the first time binding errors between representations of complex and meaningful features of real-world objects in visual working memory. These

binding errors manifested as failures to recognize which exemplar of an object from a given basic category went with which state. This suggests that even real-world objects are not stored holistically in visual working memory.

- We demonstrated that the distinctiveness of remembered objects differently affects their retrieval from visual working memory depending on a retrieval task. Specifically, the distinctiveness of memoranda does not affect simple recognition (old-new judgments), but it affects memory for object-location conjunctions, such that observers confuse where which object has been presented when the objects are similar.

Theoretical significance

The theoretical significance of the current studies could be characterized by its contribution to the discussion about the representational format of visual working memory as well as models of visual working memory. It specifically adds to the understanding of how complex, real-world objects are represented and retrieved from visual working memory.

Applied significance

Working memory is a subject of high applied interest, as working memory performance is considered a powerful predictor of subsequent academic success (Alloway & Alloway, 2008) and correlates with fluid intelligence (Fukuda, Vogel, Mayr, & Awh, 2010; Unsworth, Fukuda, Awh, & Vogel, 2015). Various working memory tests are used as a diagnostic tool for assessing various neurological disorders, e.g., Alzheimer's disease (Liang et al., 2016). Our contribution to the discussion of the representational format of visual working memory can be useful to clarify what exactly visual working memory tests measure and, thus, can improve currently available tests. Also, our results could be partially used in such practice-oriented areas as User Experience/User Interface Design in order to effectively minimize working memory load during the interaction with various virtual environments.

Reliability of the research results is ensured by the use of controlled experimental procedures in accordance with the standards of psychophysics and experimental psychology. Statistical methods of data processing are selected correctly.

The data of most studies are available online on the “Open Science Framework” platform, thus, the correctness of the conclusions could be rechecked.

Statements for the defense

- Individual objects are not represented holistically in visual working memory. Rather, their meaningfully separable feature dimensions (be they basic visual properties such as color or orientation or properties of real-world objects – exemplar or state features) can be represented relatively independently in visual working memory.
- Independent feature storage can, nevertheless, be part of the more complex hierarchical organization of visual working memory. This hierarchical organization implies that the information about independent features is accessed as a primary representational format, but the availability of whole-object information (e.g., when different features belong to the same location) can be additionally used to reduce interference from different features being remembered independently. "Feature bundles" are hierarchical and core units of visual working memory.
- The access to the representation is highly dependent on the task. Interference caused by the similarity of items could affect object-location retrieval rather than object recognition. These differences in accessibility and discriminability could be explained by the difference in target-nontarget familiarity in the two tasks.

Data collection and apparatus

We conducted ten separate experiments, with 208 observers taking part in these experiments. The observers were tested at the Cognitive Research Laboratory (HSE University, Moscow, Russia). Experiments were developed and presented via PsychoPy (Peirce et al., 2019) for Linux Ubuntu on a standard CRT monitor with a refresh frequency of 75 Hz and 1,024 × 768-pixel spatial resolution.

Personal contribution

The dissertation uses the results obtained by the author personally in three empirical studies. The content of the dissertation reflects the author's personal contribution to published works, a theoretical review of studies was independently conducted, experimental data was planned and collected, data processing, analysis and interpretation was carried out; reports for conferences and publications on the main results of the study have been prepared by author.

Approbation of the research

The results of the present work have been publicly presented in talks and posters:

- Vision Sciences Society 16th Annual Meeting (2016, St. Pete Beach, USA), *The compression of bound features in visual short-term memory*
- Theoretical and applied problems of cognitive psychology (2016, Russia), *Compression and binding in visual short-term memory*
- Vision Sciences Society 17th Annual Meeting (2017 St. Pete Beach, USA)*, An effect of categorical similarity on object-location binding in visual working memory*
- Vision Sciences Society 18th Annual Meeting (2018, St. Pete Beach, USA), *Real-world objects are not stored in bound representations in visual working memory*
- 41st European Conference on Visual Perception (2018, Trieste, Italy)*, Object distinction and object-location binding as sources of interference in visual working memory*
- Virtual Working Memory Symposium (2020, online, USA), *Different features are stored independently in visual working memory but mediated by object-based representations*
- Virtual Working Memory Symposium (2021, online, USA), *What allows an object to escape attribute amnesia?*
- 43rd European Conference on Visual Perception (2021, online)*, JURICS Stimulus base - Joint Universal Real-world Images with the Continuous States*

Six colloquium talks have been presented in the HSE Laboratory for Cognitive Research (2019), Cognitive Research Seminar HSE University (2019), Vision and Memory Laboratory at University of California San Diego (2019), Laboratory of Psychophysics École polytechnique fédérale de Lausanne (2020), Visual Attention Lab, Harvard (2021), Fougnie Lab, NYUAD (2021).

2. Features vs. objects as units of visual working memory

Article selected for the defense: Markov, Tiurina, Utochkin, 2019

In their foundational study, Luck and Vogel (1997) found that the total number of presented variable features does not affect performance in change detection and concluded that objects rather than features are units of visual working memory and estimated visual working memory capacity as about 3-4 objects (see also, Cowan, 2001). These results support the "strong" object hypothesis, which states that visual working memory is restricted only by a number of objects, while features do not affect capacity independently from the objects and can only be lost when the whole object is forgotten. These findings are also in line with 'slot' models of visual working memory (Rouder et al., 2008). However, these strong claims of Luck and Vogel (1997) that the number of objects is the main limiting factor of working memory capacity were not reliably supported by later studies (Olson & Jiang, 2002; Oberauer & Eichenberger, 2013; Hardman & Cowan, 2015; Wheeler & Treisman, 2002; Fougnie & Alvarez, 2011; Fougnie, Cormiea, & Alvarez, 2013; Bays, 2016; Bays, Catalao, & Husain, 2009; Bays, Wu, & Husain, 2011; Emrich & Ferber, 2012; Pertzov et al., 2012; Oberauer & Lin, 2017), suggesting that features rather than objects are units of visual working memory. On the other hand, object representations still seem to play a role in organizing information in visual working memory. For example, it was shown that feature recall could benefit from being presented within the same rather than different objects: multiple features of a single object are easier to recall than the same set of features separated across multiple objects (Fougnie et al., 2010; Fougnie et al., 2013). Therefore, it is important to understand how object-based benefit can occur in visual working memory along with a lot of evidence of independent feature storage.

In order to deeply investigate the relationship between memories for features from different dimensions and potential whole-object representations in visual working memory representations, we have run three experiments using a continuous report paradigm (Wilken & Ma, 2004; Zhang & Luck, 2008; Bays et al., 2009) that allowed us to estimate the capacity and precision of visual working memory representations. In each trial, we asked participants to memorize a set of items of different colors and orientations and report either the color or the orientation of a cued item (see Figure 1B). Participants had to adjust the target feature of the cued item to match the sample feature presented at that location in the original memory display. Within each experiment, we manipulated feature load orthogonally for each feature dimension. Hence, there were four possible conditions (see Figure 1A): (1) both color and orientations identical, (2) only orientation identical (colors different), (3) only color identical (orientations different), (4) all features different. Also, we included a control condition, with only one object presented on the screen (two objects in Experiment 2). In Experiment 1, colors and orientations were combined to form two-feature objects. In Experiment 2, colors and orientations were separated into spatially distinct objects. In Experiment 3, colors and orientations belonged to different but spatially overlapping objects.

Overall, we found the best performance in the condition with all identical features for both color and orientation reports (see Figure 1C). Importantly, the performance in this condition was comparable with that in the control condition with only one object presented (two separate objects in Experiment 2). When any of the feature dimensions took different values across objects, this significantly decreased performance for this feature dimension, but it did not affect performance for another dimension keeping it on the same level as in the control condition. That is, manipulating feature load within each dimension independently affected that but not the other dimension. This pattern of independence was observed in all experiments, except for Experiment 2. In Experiment 2, we found that color load decreased performance not only in color recall but also for orientation recall.

In sum, we found no cross-dimensional interference in Experiments 1 and 3, where colors and orientations were represented as features of the same objects or as features of spatially overlapping objects, which could instantiate object-like units (Rensink, 2000; Trick & Pylyshyn, 1993; Wolfe & Bennett, 1997; Xu, 2002). However, we found interference between different feature dimensions in Experiment 2, where features were divided into distinct objects by clear spatial separation. These results are in line with the hypothesis that the representational units of visual working memory are not whole objects or totally separate features but rather hierarchical representations – "feature bundles" (e.g., Brady et al., 2011). In this view, both object information and feature information are available (see also, Qian, Zhang, Liu, Lei, 2019), but on different levels of hierarchy. We suggest that features are stored independently in visual working memory, but the object level of hierarchy could play the role of a mediator, decreasing cross-dimensional interference (Oberauer & Lin, 2017) and supporting the proper allocation of available resources (Bays, 2015; Wilken & Ma, 2004).

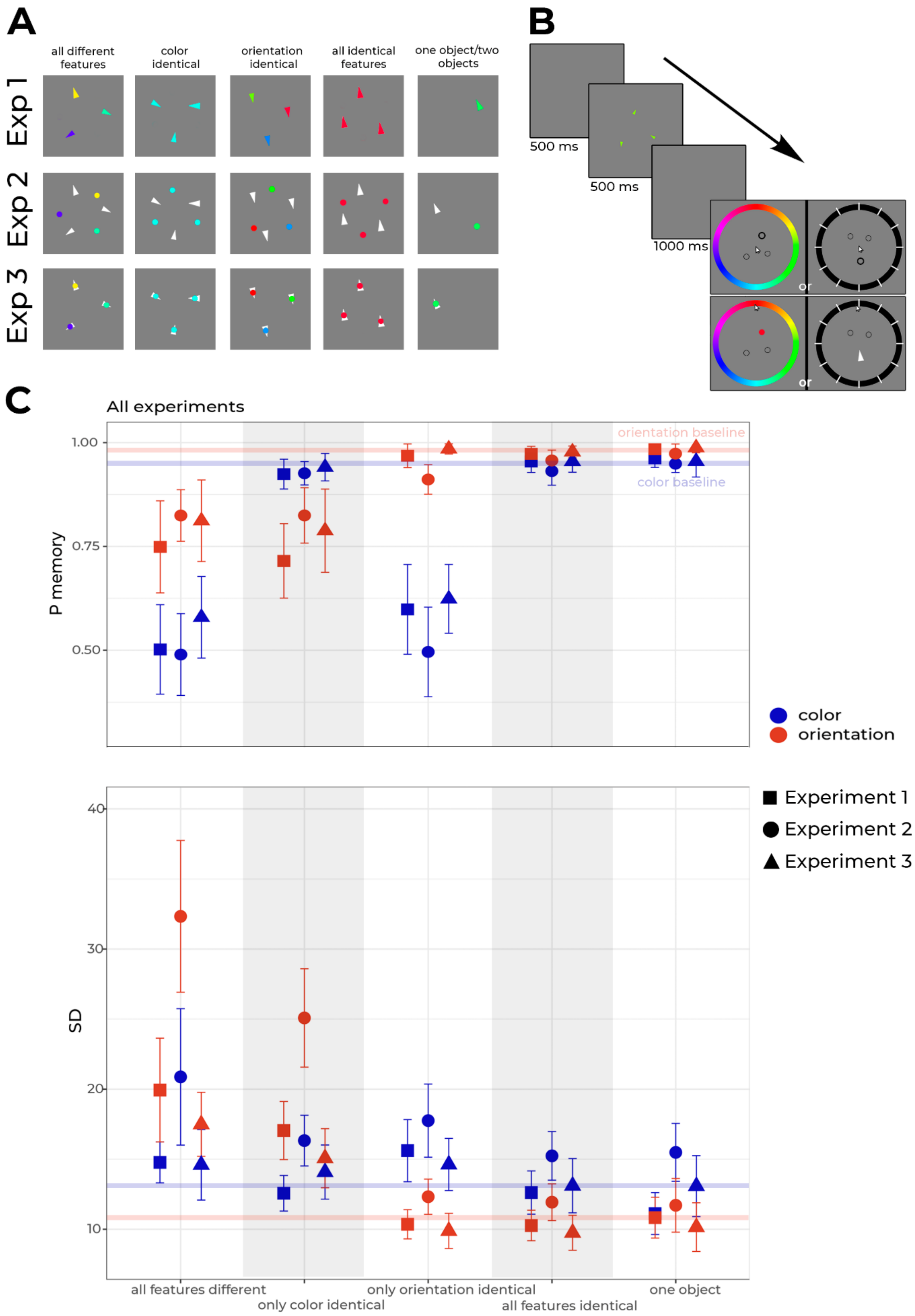

Figure 1. A: Examples of stimulus sets and conditions used in Experiments 1, 2, & 3 from Markov et al. (2019). B: The time course of a typical trial in Experiment 1. C: Results of Experiment 1-3: P_{memory} and *SD* of the mixture models as a function of Sample type and Experiment. Error bars depict 95% CIs. Adapted from Markov, Tiurina, & Utochkin 2019.

3. Representation of real-world objects in visual working memory

Article selected for the defense: Markov, Utochkin, Brady, 2021

Most of the studies investigating the representational format of visual working memory use simplistic objects with easily manipulated independent features. But how are real-world objects stored in visual working memory? According to numerous studies (Asp, Störmer & Brady, in press; Brady, Störmer, & Alvarez, 2016; Brady & Störmer, 2020; Brady & Störmer, in press; Starr et al., 2020), working memory capacity for real-world objects is not so fixed as for simple stimuli. Here, we ask: Can independence of features similar to that found for simple stimuli (Wang et al., 2017; Shin & Ma, 2017; Markov, Tiurina & Utochkin, 2019) be observed for real-world objects? Can we remember complex real-world features but fail to bind them correctly? Or can we forget these features independently of each other? This question has been previously studied for visual long-term memory (Balaban, Assaf, Arad Meir, & Luria, 2020; Brady, Konkle, Alvarez, & Oliva, 2013; Spachtholz & Kuhbandner, 2017; Utochkin & Brady, 2020). Findings suggest that features of real-world objects (e.g., colors or specific states or poses in which objects appear) can be independently lost from visual long-term memory (Brady, Konkle, Alvarez, & Oliva, 2013). In another recent study (Utochkin & Brady, 2020), it was found that observers have a good memory for two complex features of real-world objects, state features (e.g., book open and book closed, see Figure 2A) and exemplar features (e.g., John Tolkien's "The Hobbit, or There and Back Again" book and William James' "The Principles of Psychology"). Although we refer to state and exemplar as complex features or object properties, they are not similar to the basic features, e.g., as described in the Feature Integration Theory, such as color or orientation (Treisman, 1996). The discrimination of these visual features is quite complex, and different kinds of exemplar or state changes can be provided by various changes in visual appearance and semantic relationships. However, distinguishing between different states and different exemplars of the same object category are important everyday tasks. Thus, in the present chapter, we study these properties of real-world objects while investigating the nature of these features is the topic of further research. At the same time, "swap" errors (participants report incorrect state-exemplar combinations) took place frequently, suggesting that the state information and the exemplar information are represented independently and not in a holistic manner.

Since the evidence of feature independence has been previously observed in visual long-term memory, we can ask: Is this a property of long-term memory organization that leads to the features being stored and/or forgotten independently? Or does the information about objects is consolidated into long-term memory as a set of independent features? In other words, can feature independence do with the way visual working memory represents real-world objects? We addressed this question in our following study.

In order to investigate real-world object representations in visual working memory, we adapted the paradigm from Utochkin and Brady (2020). In that study, observers had to memorize lists of objects from various basic categories. Each category was represented by two exemplars (e.g., coffee mug A and coffee mug B), each shown in the same state (e.g., both coffee mugs full) or in different states (e.g., empty coffee mug A and full coffee mug B). The observers were then asked to recall in which state each exemplar had been presented. Utochkin and Brady (2020) found that observers had no difficulties reporting exemplar-state combinations when the original states were the same, but the observers were at the chance when the original states were different (although there was evidence that the observers remembered the exemplars and the states on their own).

In the present study, we used a stimulus set of object images from different basic categories (the original stimulus set from Brady et al., 2013 with an additional subset of images never used before), where each category was represented by four images, two different exemplars in two different states. For instance, a whole red apple, a whole green apple, a cut red apple, and a cut green apple (see Figure 2A). Critically, we were interested in how often observers could correctly remember both exemplars and states of presented objects but incorrectly assign states to the exemplars making a «swap» or a binding error. For instance, if the whole green apple and the cut red apple were presented and an observer reports having seen the whole red apple and the cut green apple, this is what we label a "swap".

Experiments 1 and 2 consisted of the exemplar memory task and the exemplar-state memory task. In the exemplar-state task, two exemplars from one category and two exemplars from another category were presented in a memory set. Within each category, the exemplars could be presented in the same state or in different states. At test, memory for only one of the categories was tested. Each test pair included two possible states of the same exemplar. The observers had to choose a state in which a given exemplar had been presented in the memory set. Following the logic of Utochkin and Brady (2020), iIf real-world objects are stored not as holistic representation in visual working memory, we expect worse performance for objects originally presented in different states because observers have to remember not only exemplars and states but also to correctly "bind" particular states with particular exemplars. In contrast, the need to bind is not a big difficulty if the exemplars are originally presented in the same state: In this case, remembering a common state for both exemplars is sufficient to perform the state-exemplar task. The exemplar task was used to obtain baseline performance for exemplar memory. In this task, the memory set also included four items, two exemplars from two categories. At test, two pairs of objects from one of the categories were shown, each pair including one old and one new exemplar. The participants had to choose exactly an old exemplar in each pair. In Experiment 1, the exemplar task and the exemplar-state task were presented in separate blocks. In Experiment 2, trials from exemplar and exemplar-state tasks were randomly mixed with discouraging observers from focusing on specific exemplar or state features.

In both experiments, the observers demonstrated good memory for exemplars, as shown by the exemplar task (86% correct). They also had a reasonably good memory for states, as they were mostly correct at choosing two same states when the objects had been presented in the same states, and they were correct at choosing two different states when the objects had been presented in different states (see Figure 2C). However, in terms of reporting exemplar-state conjunctions, performance was significantly worse in the condition where items were presented in different states compared to the same states. Interestingly, in about 15% different-state trials, observers successfully reported the states as being different but chose wrong the exemplars for these two states (committed 'swaps').

These results indicate that, even when observers have some memory for exemplars and states separately, the binding errors occurred between these two kinds of features. In Experiment 3, we tested how location update at the test could influence binding errors. In two conditions, we presented items at the test at the same location as during the presentation, or locations of tested items were switched. We found that the location update did not cause more binding errors but decreased overall performance. This suggested that during location update, exemplars and states could not be bound independently to the locations and that location updating appears to act on the unitized, fully bound representations.

Overall, our results suggest that real-world objects are also prone to binding errors, like simple objects, confirming the basic non-holistic nature of object representations in visual working memory.

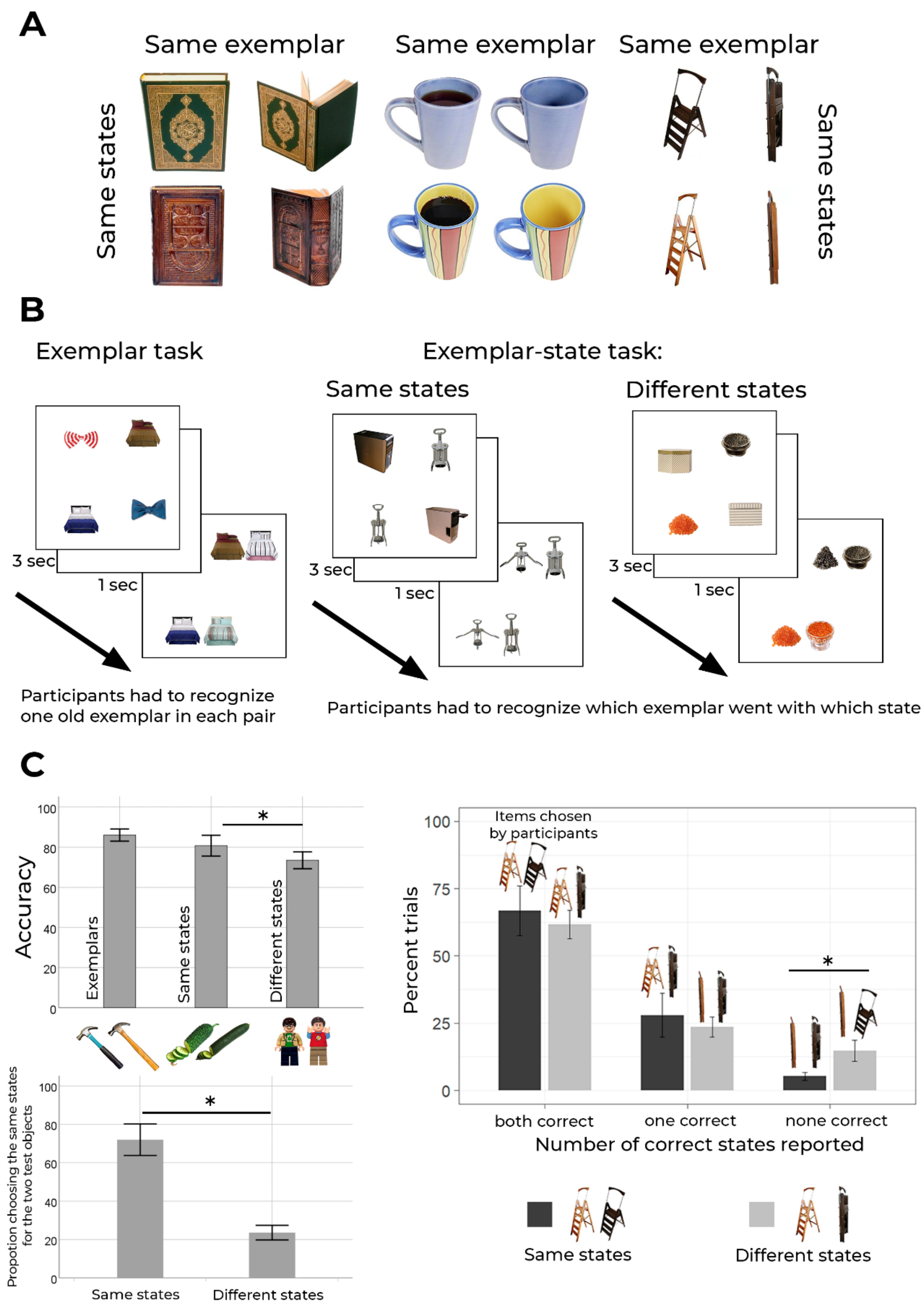

Figure 2. General methods and principal results by Markov, Utochkin, & Brady, 2021. A: Example of two different exemplars in two different states. B: The time course of a typical trial in Experiment 1 in the exemplar–state task and the exemplar task. C: Results of Experiment 1: Overall accuracy, State memory accuracy, and choosing both, one, or no correct states for exemplars. Error bars depict 95% CIs. Adapted from Markov, Utochkin, & Brady, 2021.

4. Retrieval of information from visual working memory

Article selected for the defense: Markov, Utochkin 2022

As can be seen from the previous chapter, interactions between different objects and their features can give us useful information about the way information in visual memory is organized. Here, we further investigate interactions between objects in visual working memory and focus on two aspects. First, real-world objects are typically remembered, not in isolation, that is, context is important. Visual working memory is frequently considered a spatially organized system (Logie, 2003; Magen & Emmanouil, 2019). Thus, we store information not only about what we saw but also about where. Spatial information plays an important role in the binding process (Swan & Wyble, 2014; Treisman, 1996) and is relevant for many tasks involving visual working memory. Remembering objects at locations (that we term object-location memory) is also prone to binding errors similar to those between different features of multiple objects (such as exemplar and state features), but they occur between objects representation and locations (Bays et al., 2009; Dent & Smyth, 2005; Hollingworth & Rasmussen, 2010; Pertzov, Dong, Peich, & Husain, 2012; Postma & De Haan, 1996; Treisman, 1996; Toh, Sisk, & Jiang, 2020; but see Pratte, 2019). For example, when a person puts a smartphone in their left jeans pocket and a wallet in their right jacket pocket, the person can subsequently recall which items they put in the pockets but can swap their locations in memory and look for the wallet in the left jeans pocket. These errors suggest that memories for objects and for scene context in which those objects have been seen are not unitized. Other than that, representations of objects can interfere with each other (feature binding errors described in the previous chapter is one example). The degree of interference as a function of inter-object relationship strongly depends on a set of factors termed distinctiveness (Hunt, 2006). Previous studies show that item distinctiveness affects performance in visual working memory tasks, but the direction of these effects can be the opposite. While some studies have suggested that high inter-item distinctiveness increases subsequent memory performance, others have suggested that high distinctiveness decreases it (Cohen et al., 2014; Jiang, Lee, Asaad, & Remington, 2016; Lin & Luck, 2009; Sims, Jacobs, & Knill, 2012). The important theoretical question that we address in the current study is how distinctiveness influences both object and object-location memory. That is, we ask how inter-item structural relationships affect object retrieval in context-free (simple object recognition) and context-dependent tasks. Does low object distinctiveness disrupt proper object-location binding, causing more swap errors? Why do swap errors for location occur? Are there significant differences between retrieval information about objects and object-location bindings?

In a series of experiments, we investigated the influence of item distinctiveness on object memory, location memory, and object-location memory. We manipulated the distinctiveness of items by presenting objects that belonged to the same or different basic categories. In Experiment 1, we presented three objects located around an imaginary circumference and asked observers to remember them and their locations (see Figure 3A). After a one-second blank retention interval, two test items were presented (always from the same category regardless of the presentation condition): one item was old (already shown in the set), and another was new. Observers were asked to choose the old item. On the next step, the observers had to localize the chosen item along a circumference so that it matched the location of this item in the original display. We measured percent correct answers in the recognition task. For the localization task, we used a modification of the mixture model (Zhang & Luck, 2008) "swap model" (Bays et al., 2009). The outcome of the swap model is a set of parameters supposed to reflect various aspects of visual working memory. These parameters include the P_{memory}, the *SD* or precision of a correctly reported memory representation and also the P_{swap} reflecting the probability of reporting a really presented but not probed item. While the P_{memory} and the *SD* are characteristics of location memory (how likely and how precisely observers recall locations themselves), the P_{swap} reflects specific object-location failures (how often observers recall an object at a wrong location).

We found in the result of Experiment 1 that distinctiveness did not affect performance in the recognition task and did not affect the precision of item localization (see Figure 3B). By contrast, we found that observers made more swap errors for low-distinctive items in the localization task. Additional analysis demonstrated that this increment in non-target reports was not caused by simple forgetting of elements. We conclude that reduced item distinctiveness impaired an ability to specifically recall object-location bindings rather than abilities to recognize objects or remember locations.

In Experiment 2, we basically replicated the design of Experiment 1, but this time we tested object-location and location memory without the recognition task in order to remove a potential interference of recognition with localization. We also added a condition where we could test "pure" location memory with reduced demands on object-location binding. We found the same results as in Experiment 1 and additionally showed that the precision of "pure" location memory was the same as in other conditions (those requiring remembering object-location conjunctions). Therefore, we conclude that task demands on remembering objects or binding them to locations did not affect the precision of localization.

In Experiments 3A and 3B, we considered two plausible explanations for the distinctiveness effects observed in Experiments 1 and 2. First, poor item distinctiveness could impair object-location memory in general and non-specifically. High demands on visual working memory to store low-distinctive items could cause a trade-off between remembering objects and object-location conjunctions. Second, object-location retrieval depends on how easily a particular target representation can be separated from non-target representations based on their inter-object differences and spatial cues. The main difference between these two accounts is what they predict about non-target reports. The first account predicts that if there are several items varying in distinctiveness from item to item, then non-target reports should occur randomly regardless of similarity between particular items. The second account predicts that the non-target reports specifically depend on item-to-item similarity: There should be more "swap" errors between more similar items.

In Experiment 3A, we tested object-location memory for four objects from either one, two, or four categories (Figure 3C). Instead of using a continuous localization report (as in Experiments 1 and 2), we used a four-alternative forced choice of an object by a location cue. That is, after the retention interval, the location of one of the presented objects was cued, and the observers had to choose which of the four presented objects had been presented at the cued location. In Experiment 3B, the same sets of objects were tested for recognition in a two-alternative choice task (same as in the recognition stage of Experiment 1). Similar to the previous two experiments, distinctiveness was found to affect performance in the object-location task (Experiment 3A), such that observers committed more object-location errors ("swaps") when a memory display consisted of four objects drawn from one category. At the same time, no cost to recognition performance was found (Experiment 3B). We then took a closer look at the critical condition where four objects were from two different categories, that is, there always were non-targets that were more similar to the target and two non-targets that were more dissimilar with the target. Incorrect reports (swap errors) were distributed unevenly between non-targets as a function of their similarity to the target. We found that the non-targets from the same category as the target were chosen more often than any of the foils from the different category (Figure 3D). Therefore, we found that object-location memory is affected in a specific way which is defined by item-to-item similarity.

The results of our experiments show an interesting dissociation between the effects of object distinctiveness on simple recognition (no effect) and on object-location memory (less distinctive objects are more likely swapped). To account for this dissociation, we suggested that the crucial differences between retrieval of the object and object-location information could be explained by existing models of visual working memory as noisy representations or familiarity signals competing at multiple stages of processing (e.g., Oberauer & Lin, 2017; Schneegans & Bays, 2017; Swan & Wyble, 2014; Schurgin, Wixted, & Brady, 2020). In line with some of the previous models of attention and visual search (Duncan & Humphreys, 1989), the distinctiveness of the target and non-target plays a crucial role also in memory tasks. Since representations are all noisy, then distinctiveness affects how separable representations are relative to the noise. Here, the difference between the tasks arises from how exactly noisy familiarity judgments are made. In the 2-AFC recognition "old-new" task, the familiarity signal produced by the target is compared against that produced by a foil at the test. In this case, the distinctiveness of encoded items does not strongly affect performance in the recognition task because any single target produces a stronger signal than a foil, while comparison between different targets is not required. In the object-location task, observers had to discriminate between competing noisy representations of all items linked to various locations. In Experiment 3A, non-target items from the same category as the target were chosen more frequently than non-targets from the different category because the location cue elicited more familiarity with the former non-target. An extended signal detection model depicted in Figure 3E illustrates this theoretical idea (Macmillan & Creelman, 2005; Schurgin et al., 2020). Target-nontarget distinctiveness defines the probability of a non-target response. A location cue causes a familiarity strength for each test item drawn from a certain Gaussian distribution. The stronger the familiarity distribution is shifted to the right, the more likely a corresponding item is chosen as a target. The separation between the distributions is defined by the distinctiveness of the test items. It is easy to see that the familiarity distribution of same-category non-targets has more overlap with the target distribution than the distribution of different-category non-targets. That is, in an individual trial the same-category non-target has a greater chance to produce the strongest familiarity than any of the different-category non-targets. We, therefore, suggest that object-location errors arise due to representational competition during retrieval. The visual working memory representation itself can be considered to be a noisy signal induced by a retrieval cue (such as a location cue) which is compared against other signals provided by test alternatives. This theoretical view on visual working memory representations does not contradict our previously mentioned ideas of hierarchical bundles: These familiarity signals can arise to represent different levels of this hierarchy from separate features to objects and to groups and sets.

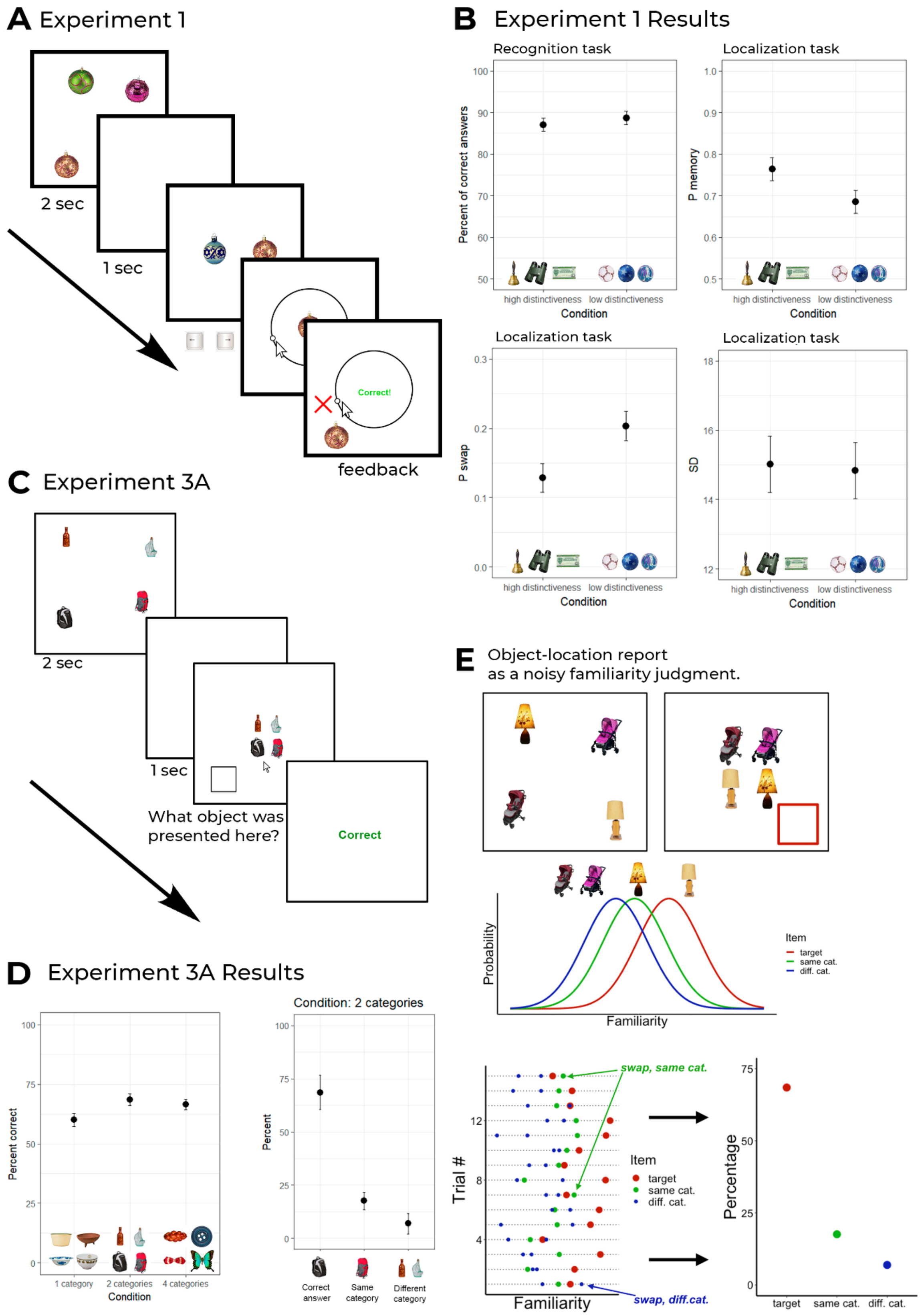

Figure 3. A: The time course of a typical trial in Experiment 1. B: Results of Experiment 1 for the recognition task (percent correct) and the localization task (P_{memory}, P_{swap}, SD). Error bars depict 95% CIs. C: The time course of a typical trial in Experiment 3A. D: Results of Experiment 3A. Percent correct for all conditions and percent of correct answers for the condition with two categories. E: Object-location report as a noisy familiarity judgment. Adapted from Markov, & Utochkin, 2022.

Conclusion

In the series of studies, we investigated the structure of visual working memory units and their interactions. We found that the units are not holistic object representations and also not completely isolated features but rather hierarchically organized feature "bundles" (Brady et al., 2011). This means that visual working memory representations in different tasks can benefit from the independence of feature representation and from their organization into whole objects. Our results suggest that these "feature bundle" structures could be applied to both simple geometrical stimuli and complex real-world objects and act as core units of visual working memory.

We suggest that information is not stored on the "shelves" in visual working memory and that retrieval of information from visual working memory depends on the task requirements on retrieval. The visual system can retrieve the information from different levels of visual working memory representations and use this information according to the current task. The visual system highly relies on competitive, noisy familiarity signals caused by retrieval cues and test alternatives available at the recall stage. In a simple recognition task (2AFC), the familiarity of the target is compared against a presented novel foil at test, and observers decide whether this or that item looks more familiar. In the tasks where the object should be remembered (bound) along with its contextual information such as location, the familiarity of the target competes with representations of other to-be-remembered items causing considerable interference between the items. Our results are in line with and elaborate the current models of visual working memory - resource-based models (e.g., Bays & Husain, 2008), interference model (Oberauer & Lin, 2017), target confusability competition model (Schurgin, Wixted, & Brady, 2020), by demonstrating similar effects for simple features and complex objects. Thus, overall, our findings suggest that visual working memory representations are flexible, hierarchical, and highly dependent on the current task.

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