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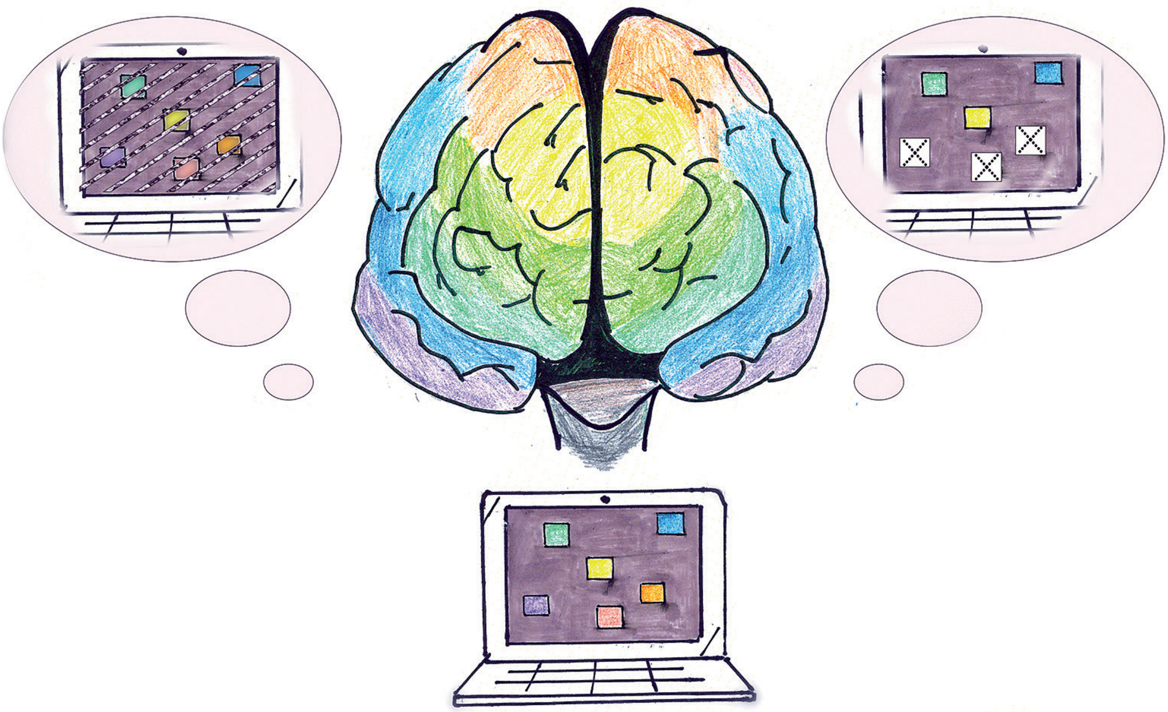
Chaoxiong Ye

Visual Working Memory Resource Allocation Mechanism in Consolidation and Maintenance Phase



JYVÄSKYLÄN YLIOPISTO

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Esitetään Jyväskylän yliopiston informaatioteknologian tiedekunnan suostumuksella
julkisesti tarkastettavaksi yliopiston Agora-rakennuksen Beeta-salissa
toukokuun 24. päivänä 2018 kello 12.

Academic dissertation to be publicly discussed, by permission of
the Faculty of Information Technology of the University of Jyväskylä,
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UNIVERSITY OF JYVÄSKYLÄ

JYVÄSKYLÄ 2018

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JYVÄSKYLÄ 2018

Editors
Marja-Leena Rantalainen
Faculty of Information Technology, University of Jyväskylä
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Publishing Unit, University Library of Jyväskylä

Cover picture: *Visual memory* by Qianru Xu.

Permanent link to this publication: http://urn.fi/URN:ISBN:978-951-39-7419-0

URN:ISBN:978-951-39-7419-0
ISBN 978-951-39-7419-0 (PDF)

ISBN 978-951-39-7418-3 (nid.)
ISSN 1456-5390

Jyväskylä University Printing House, Jyväskylä 2018

ABSTRACT

Ye, Chaoxiong
Visual working memory resource allocation mechanism in consolidation and maintenance phase
Jyväskylä: University of Jyväskylä, 2018, 125 p. (+ included articles)
(Jyväskylä Studies in Computing
ISSN 1456-5390; 280)
ISBN 978-951-39-7418-3 (nid.)
ISBN 978-951-39-7419-0 (PDF)
Finnish summary
Diss.

Visual working memory (VWM) is a system for actively maintaining visual information to meet the needs of an ongoing task. It allows individuals to store visual input information from a complex outside environment and provides storage space as an information buffer platform to help integrate information into a continuous visual experience. This research examined the consolidation and maintenance phase of the VWM resource allocation mechanism.

Four aspects of this issue were investigated. First, resource allocation in VWM consolidation was investigated for different materials, and it was determined whether VWM resources were allocated in a serial manner for orientation materials but in a limited-capacity parallel manner for colour materials. Second, voluntary resource allocation during the consolidation process was investigated and a two-phase model to explain resource allocation was proposed. In addition, the results suggested that the individual's VWM capacity has an impact on this two-phase process. Third, the effect of distribution location of memory items on VWM resource allocation was investigated, and it was found that more attention resources are available when items are spread across two hemifields. Fourth, the resource allocation in the maintenance phase was investigated, and it was found that participants could use dimension-based internal attention to reallocate resources to a particular dimension of representations. Overall, this research used the event-related potentials technique to solve the debate regarding the manner of VWM consolidation; proposed the two-phase model to explain the previous contradictory results regarding voluntary VWM resource allocation; explored the advantage of a bilateral field and developed a new paradigm to investigate dimension-based internal attention. Therefore, this research provided much new evidence and directions regarding resource allocation in the VWM consolidation and maintenance phase.

Keywords: visual working memory, resource allocation, consolidation, maintenance, two-phase

Author Chaoxiong Ye
Faculty of Information Technology
University of Jyväskylä, Finland

Supervisors Professor Pertti Saariluoma
Faculty of Information Technology
University of Jyväskylä, Finland

Professor Tapani Ristaniemi
Faculty of Information Technology
University of Jyväskylä, Finland

Professor Qiang Liu
Research Center of Brain and Cognitive Neuroscience
Liaoning Normal University, China

Professor Fengyu Cong
Department of Biomedical Engineering
Dalian University of Technology, China

Reviewers Dr. Jaana Simola
Helsinki Institute of Life Science, Neuroscience Center
University of Helsinki, Finland

Dr. Stephen Rhodes
Department of Psychological Sciences
University of Missouri, United States

Opponents Professor Robert Logie
School of Philosophy, Psychology and Language Sciences
University of Edinburgh, UK

ACKNOWLEDGEMENTS

Reflecting back on my PhD experience, it has been a difficult but surprising journey. I arrived in Finland in October 2015. Since this is the first time I lived alone in a foreign country for a long time, I have faced many difficulties. Fortunately, the people around me have made my journey possible.

First of all, I would like to express my sincere gratitude to my main supervisor, Prof. Pertti Saariluoma. He is one of the most knowledgeable people I have ever met; he is full of information about philosophy, psychology and cognitive science. Over the past two years, we have had one or two discussions every week. He showed me not only how to publish articles but also how to find a direction for my research. Without his help, my dissertation would not have been able to transform from a rough 50 pages to the current version. Although the process has been stressful, I am very proud to have finished my dissertation in the present way. Under his supervision, it has been an unforgettable experience.

I am also very grateful to my second supervisor, Prof. Tapani Ristaniemi, who provided me the chance to study here. During the past few years, he has always looked after my studies as well as my daily life here in Finland. Whenever I faced a problem, I always sought his help, which made me able to quickly adapt to my PhD studies. Although our knowledge backgrounds are different, because of his unbelievable talent, he always quickly understood the key points of my research and gave me brilliant suggestions. Under his supervision, I have completed two publications and two manuscripts and received a mobility grant, which relieved many burdens during my studies.

Further, I cannot thank my third supervisor, Prof. Qiang Liu, enough. I met him when I was a struggling clinical psychology master’s student. He showed me a better path and encouraged me to try harder. Even though he did not work for the universities at which I received my master’s and doctoral degrees, he volunteered to guide me over the past six years. Because we are in different time zones and he is very busy in the daytime, he always woke up at 5 in the morning to discuss my work. There are almost two thousand pages of our chat records. His professionalism and profound knowledge have helped me become a researcher in this field. I could not imagine what I would have done without him.

I also would like to express my gratitude to my fourth supervisor, Prof. Fengyu Cong, who recommended that I study in Finland. In addition to providing me with great guidance regarding signal processing, he often gave me rational advice when I was frustrated. For example, due to many negative decisions and financial pressure, in February 2016 I was planning to give up my academic career to become a scuba diving instructor. He came to Finland and met me in a conference to tell me the secret of his high efficiency and encourage me to continue my studies. His wise suggestions helped me get through the hardest stages of my PhD journey.

Additionally, I am grateful for the helpful comments from two reviewers, Dr. Jaana Simola from the University of Helsinki and Dr. Stephen Rhodes from the University of Missouri, as well as to Prof. Robert Logie from the University of Edinburgh for agreeing to become my opponent in the defence.

Dr. Piia Astikainen has been one of my most important supporters at university. By chance, I began to cooperate with her in 2015. I felt unbelievably comfortable in the research group of which she was part, and she taught me how to fight for my rights and balance life and work. In 2017, I decided to start my second doctoral dissertation under her supervision, not because it was necessary for me to pursue another PhD degree for my career but because I wanted to remain a member of her group.

I must also thank four advisers who are very important to me. I have known Dayo Wong (黄子華), a philosopher, for more than 20 years. His understanding of impermanence helped me through every period of depression, and his advice helped me move past my pessimism. Han Han (韩寒) taught me the sense of responsibility that young people should have, and the importance of sticking to my own path. Yonghao Luo (罗永浩) made me understand the value of being an idealist and how to remain enthusiastic about my career and life. Finally, Jonas Hwang (黄執中) helped me see the power of critical thinking; there could be many conflicting explanations of each result, but critical thinking allows one to find the most convincing answer.

In addition, I have much appreciation for my important co-authors, Prof. Taosheng Liu, Prof. Hongjin Sun, Prof. Lingcong Zhang, Prof. Hongzhong Qiu, Dr. Zhonghua Hu, Xueqiao Li, Elisa Ruohonen, Yin Zhang, Tengfei Liang, Renning Hao and Jiachen Lu. I have learned a lot from them. I also very much thank my colleagues, Prof. Paavo Leppänen, Dr. Jarmo Hämäläinen, Dr. Tuomo Kujala and Dr. Sami Kollanus. They have taken good care of me and my studies. Likewise, I thank George R.R. Martin, Zheng, Di, Fufan, Yongjie, Deqing, Juho, Jari, Tiantian, Weiyong, Xin, Wendan, Yijian, Han, Jiadi, Xueyan, Yong, Junhan, Aleix, Mathieu, Shuhang, Menghan, Yiming, Yu, Tianyi, Jianyu, Zihan, Xiaoguang, Xiaoen and Siheng,among others, for the happy memories we shared.

Finally, I would like to thank my girlfriend, Qianru. Because of your company, I never felt lonely on my journey. After visiting 26 countries together, I’ve found that my experiences with you are the most important part of my life. You are the only one who can understand the meaning of 'the time we had'. I hope our future will be even better.

This work has been financially supported by the National Natural Science Foundation of China (no. 31571123 and no. 31600883) and the China Scholarship Council. Now I am working for the Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, China.

Reykjavik 26.4.2018
Chaoxiong Ye

LIST OF ORIGINAL PUBLICATIONS

I Renning Hao, Mark W. Becker, Chaoxiong Ye, Qiang Liu & Taosheng Liu.(2017). The bandwidth of VWM consolidation varies with the stimulus feature: evidence from event-related potentials. *Journal of Experimental Psychology: Human, Perception, and performance*. Advance online publication. doi: 10.1037/xhp0000488.

II Chaoxiong Ye, Lingcong Zhang, Taosheng Liu, Hong Li & Qiang Liu. (2014). Visual working memory capacity for color is independent of representation resolution. *PLoS One*, 9(3), e91681. doi:10.1371/journal.pone.0091681

III Chaoxiong Ye, Zhonghua Hu, Hong Li, Tapani Ristaniemi, Qiang Liu & Taosheng Liu. (2017). A two-phase model of resource allocation in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43 (10), 1557-1566. doi: 10.1037/xlm0000376

IV Chaoxiong Ye, Hong-Jin Sun, Qianru Xu, Tapani Ristaniemi, Pertti Saariluoma, Fengyu Cong & Qiang Liu. (2018). The impact of visual working memory capacity on the resource allocation in consolidation. Submitted manuscript.

V Yin Zhang, Chaoxiong Ye, Debi Roberson, Guang Zhao, Chengbo Xue & Qiang Liu. (2018). The bilateral field advantage effect in memory precision. *Quarterly Journal of Experimental Psychology*. 71(3), 749-758. doi: 10.1080/17470218.2016.1276943

VI Chaoxiong Ye, Zhonghua Hu, Tapani Ristaniemi, Maria Gendron & Qiang Liu. (2016). Retro-dimension-cue benefit in visual working memory. *Scientific Reports*, 6, 35573. doi: 10.1038/srep35573

Contribution in the articles

Article I was jointly written. I was responsible for the original version of method and result sections. Renning Hao was responsible for the original version of the other sections. Mark W. Becker and Taosheng Liu contributed to modification of the manuscript. The experiment was planned by all authors. Renning Hao and I conducted the experiments and data analysis. Qiang Liu functioned as the supervisor.

As the principal author of Article II, I was responsible for the main line of thought concerning the study, experimental design, data acquisition, data analysis and article writing. Taosheng Liu helped to design the experiment. Lingcong Zhang helped conduct the experiment. Taosheng Liu and Hong Li helped refine the manuscript. Qiang Liu functioned as the supervisor.

As the principal author of Article III, I was responsible for the main line of thought concerning the study, experimental design, data acquisition, data analysis and article writing. Zhonghua Hu and Hong Li contributed to interpretation of the data. Taosheng Liu contributed to modification of the manuscript. Tapani Ristaniemi and Qiang Liu functioned as supervisors.

As the principal author of Article IV, I was responsible for the main line of thought concerning the study, experimental design, data acquisition, data analysis and article writing. Qianru Xu and Hong-Jin Sun contributed to modification of the manuscript. Pertti Saariluoma, Tapani Ristaniemi, Qiang Liu and Fengyu Cong functioned as supervisors.

Article V resulted from joint collaboration. Yin Zhang and I were responsible for the experimental design and programme. Yin Zhang and Chengbo Xue collected the data. Yin Zhang and I conducted data analysis together. Yin Zhang was responsible for the main content of the manuscript. The manuscript was modified by all authors. Qiang Liu functioned as a supervisor.

As the principal author of Article VI, I was responsible for the main line of thought concerning the study, experimental design, data acquisition, data analysis and article writing. Zhonghua Hu helped design and conduct the experiments. Zhonghua Hu and Maria Gendron helped refine the manuscript. Tapani Ristaniemi and Qiang Liu functioned as supervisors.

FIGURES

TABLE

LIST OF ABBREVIATIONS

ACT-R	Adaptive control of thought—rational
aLMT	Activated long-term memory
BFA	Bilateral field advantage
CDA	Contralateral delay activity
EEG	Electroencephalographic
EPIC	Executive-process/Interactive-control
ERP	Event-related potentials
FoA	Focus of attention
HEOG	Horizontal electrooculogram
ICS	Interactive cognitive subsystems
ISI	Inter-stimulus interval
LT-WM	Long-term working memory
RAM	Random access memory
RDEI	Retro dimension benefit index
VEOG	Vertical electrooculogram
VWM	Visual working memory
VSTM	Visual short-term memory
WM	Working memory

CONTENTS

1 GENERAL INTRODUCTION

1.1 Working memory

Working memory (WM) is a system for temporary maintenance and operation of information (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Logie, 2014; Logie & Gilhooly, 1998). The field of WM was defined by the seminal article of Baddeley and Hitch (1974). In early studies, WM was also called 'short-term memory' or 'primary memory' (Jonides et al., 2008). WM has a storage function similar to short-term memory, but the latter simply keeps information for a short time, while the former is able to control and manipulate internal representations based on the purpose of the task (Postle, 2006). Thus, the function of WM goes beyond the storage function of short-term memory.

For more than 50 years, research has shown that WM plays an important role in language, learning, reasoning, problem solving, decision-making and other higher cognitive activities (Anderson, 1985; Capon, Handley, & Dennis, 2003; Fedorenko, Gibson, & Rohde, 2006; Nobre et al., 2004). Thus, WM studies have had a great influence on cognitive psychology, developmental psychology and neuroscience (Baddeley, Cocchini, Della Sala, Logie, & Spinnler, 1999; Beschin, Cocchini, Della Sala, & Logie, 1997; Caggiano, Jiang, & Parasuraman, 2006; Gilhooly, Wynn, Phillips, Logie, & Della Sala, 2002; Y. Jiang, Haxby, Martin, Ungerleider, & Parasuraman, 2000; Logie & Pearson, 1997; Phillips, Gilhooly, Logie, Della Sala, & Wynn, 2003). Individuals' WM capacity is strictly limited, which limits their information processing capacity. As a result, WM could be described as limited design thinking. The capacity limitation of WM is an important interaction problem in the field of engineering design (Anderson, Farrell, & Sauers, 1984; Saariluoma, 2005).

The number of studies regarding memory rose dramatically in the 1950s. At this time, the earlier concept of short-term memory led to the development of the concept of WM. Early studies on short-term memory focused on individuals' WM capacity, and their main concern was how many units could be maintained in WM tasks. It is well known that humans can store huge amounts of information in long-term memory, and it was determined that individuals could store large amounts of information in their long-term working memory as well (Ericsson & Kintsch, 1995). For example, blindfolded chess players can remember the locations of thousands of pieces (Saariluoma, 1991; Saariluoma & Kalakoski, 1998) and taxi drivers can learn the street information of a huge city (Kalakoski & Saariluoma, 2001). However, short-term memory is considered to be severely limited. G. A. Miller (1956) found that the information an individual can remember is likely limited to 7 ± 2 objects. In addition, Sperling's (1960) partial report found that individuals' sensory memory capacity is about 9 letters. These limitations of short-term memory severely limit humans' advanced cognitive processes (Anderson et al., 1984; Cowan, 2001).

1.2 WM model

In the well-known Atkinson-Shiffrin memory model (also known as the multi-store model), short-term memory is considered a working system (Atkinson & Shiffrin, 1968). The purpose of the multi-store model is to explain the basic structure and function of memory. It proposes three independent stages of memory: sensory memory, short-term memory and long-term memory. External stimuli are passed to the 'sensory register', where external input signals are transformed into chemical and physical signals for subsequent processing. After sensory registration, the information is transmitted to the short-term memory system, where it is encoded, rehearsed and retrieved. Then, appropriate and reasonable responses can be output from the system. However, short-term memory can only store information for a short time; memorising information for the long term is performed by the long-term memory system. The long-term memory system is activated and retains information if information is repeatedly received. Once remembered, the information will be retained for a while, but if it is not reinforced over time, the individual will forget it. As a result, information in the long-term memory system is a stable representation of external stimuli. Here, the short-term memory system acts as (1) a buffer between sensory registration and long-term memory and (2) processor of information that is about to enter long-term memory.

Craik and Watkins (1973) challenged the function of short-term memory, suggesting that transfer of information from short-term memory to long-term memory after rehearsal could not be guaranteed and that the persistence of memory traces is only a function of processing depth. Individuals learn better with deeper processing. Neuropsychology studies also challenged the multi-store model. For example, short-term memory is considered to be a key working system for learning; if it is damaged, learning will be difficult. Shallice and Warrington (1970) found that, although the capacity of short-term memory was decreased in patients with disabilities, they still had normal long-term memory that enabled them to learn. This phenomenon cannot be explained by the multi-store model of memory. Based on these issues, Baddeley and Hitch (1974) proposed a multicomponent WM model, which is the most widely disseminated model of WM. Since then, researchers have begun to propose different models.

Baddeley and Hitch's (1974) model utilizes part of the multi-store models and applies the idea of multilevel storage to WM. The multicomponent WM model suggests that WM is a complex system composed of different independent components and three subsystems: a phonological loop, visuo-spatial sketchpad and central executive system. The central executive system plays a role in controlling WM, ensuring that (1) relevant information and processes are focused on and irrelevant information is suppressed, (2) various processes in charge of complex tasks are integrated and (3) WM content is monitored. The phonological loop and visuo-spatial sketchpad are storage systems. The former is used to store and rehearse verbal information and plays an important role in remembering words, while the latter is responsible for maintenance and control of visual information such as spatial and object information (Baddeley, 1992, 2012; Baddeley & Hitch, 1974; Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002; Doherty & Logie, 2016; Logie, Cocchini, Delia Sala, & Baddeley, 2004).

However, new evidence shows that information in the phonological loop and information in the visuo-spatial sketchpad seem to interfere with each other, which cannot be completely explained by the original multicomponent model (Logie, Della Sala, Wynn, & Baddeley, 2000; Saito, Logie, Morita, & Law, 2008). In their recent follow-up studies, the develops of the original model improved it by adding a subsystem called 'episodic buffer' (Baddeley, 2000; Baddeley, Allen, & Hitch, 2010; Repovs & Baddeley, 2006). This system can integrate information from WM and long-term memory and store representations by multi-dimensional coding. As the interaction interface between the other three subsystems and the long-term memory system in WM, the episodic buffer explains the interaction between WM and long-term memory in the original model with three subsystems (Figure 1a). The multicomponent model suggests that when each component operates within its own capacity, concurrent task demands have little impact on memory performance, but when components are functioning beyond the limits of their capacity, concurrent tasks have a cost (Duff & Logie, 1999, 2001; Logie & Duff, 2007).

The multicomponent WM model has been accepted by many researchers at present (Gooding, Isaac, & Mayes, 2005; Nobre et al., 2013; Rudner, Fransson, Ingvar, Nyberg, & Ronnberg, 2007). The subsystems have been supported by previous research. For example, Baddeley, Thomson and Buchanan (1975) investigated the WM structure using a dual-task paradigm. They found that there was selective interference between the two tasks. When the participants performed two tasks at the same time, such as two visual tasks, their performance of both decreased significantly. However, there was no interference between visual tasks and verbal tasks. The results show that the resources occupied by the same kinds of tasks are derived from the same WM subsystem, while the resources occupied by visual and verbal tasks belong to two different subsystems (Baddeley et al., 1975).

Another influential WM model is the unitary-store or embedded-process model proposed by Cowan (1998, 2001, 2012). The model suggests that WM is not an independent system, but part of long-term memory. The information stored in WM is part of the memory representations that have been activated in long-term memory. The WM structure consists of two embedded levels. The first level includes representations of activation in long-term memory (activated long-term memory, or aLTM). This activation is a subset of all of long-term memory. The second level, known as the focus of attention (FoA), has limited capacity and can only accommodate about four representations that have been activated in long-term memory (Figure 1b). However, the capacity limitation is presumed to be an individual characteristic that varies in the population. Based on this model, individuals could control their attention to focus on four items at any time. If the attention is transferred from original representations to other new representations, the information that is originally the FoA will be converted to aLTM. The aLTM itself has no capacity limitation, but information in this state is prone to decline with time, and it is vulnerable to interfering information. Thus, the WM is considered to be a cognitive process that retains information in an unusually accessible state.

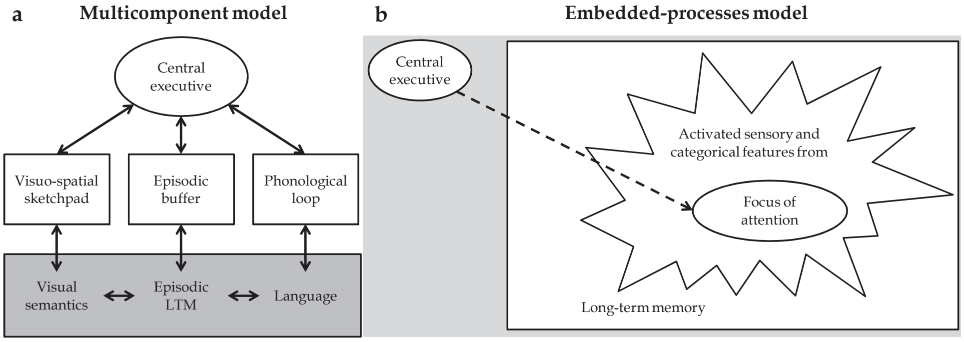

FIGURE 1 The structure of the (a) multicomponent WM model and (b) embedded-process model.

McElree (1996, 2006) extends the embedded-process model, proposing that only one representation (the one that was last noticed) at a time could be the FoA. The possibility of accessing a representation in aLTM is equal to each other, but different representations are remembered with varying strength. Representations that were focused on recently are stronger. Only the most recently noticed representation is in the FoA state; other representations that have been noticed before have varying strength but are scattered in the aLTM state (McElree, 1996, 2006).

Later, Oberauer (2005) divided the FoA into two parts, the direct-access region and narrow focus of attention. The direct-access region is part of the limited capacity of WM. Its function is to provide a set of independent information that can be directly accessed. The information stored in the narrow FoA is a representation selected from the direct-access region for the next cognitive activity (Oberauer, 2005).

The focuses of the multicomponent WM model and embedded-process model are different; the multicomponent model emphasizes the modality specificity of different information, while the embedded-process model emphasizes the focus of attention and limitations of central processing capacity. However, both models believe that the storage of verbal and visual information has modality specificity. In addition to these models, which are the two most influential WM models, a number of WM models with varying structure have been proposed (Miyake & Shah, 1999), such as the Interactive Cognitive Subsystems (ICS) model (Barnard & Teasdale, 1991), long-term working memory (LT-WM) framework (Ericsson & Kintsch, 1995), Executive-Process/Interactive Control (EPIC) model (Meyer & Kieras, 1997), 'controlled attention' framework (Kane, Bleckley, Conway, & Engle, 2001) and theory of working memory developed within the Adaptive Control of Thought—Rational (ACT-R) framework (Anderson, 2014).

In addition to the WM models, a large number of studies have been carried out on WM. Previous studies of WM suggest that limited capacity is one of the main hallmarks of WM and that individual differences in measures of WM capacity are correlated with differences in fluid intelligence, reading comprehension, and academic achievement (Alloway & Alloway, 2010; Daneman & Carpenter, 1980; Fukuda, Vogel, Mayr, & Awh, 2010; Kane et al., 2001; Unsworth, Fukuda, Awh, & Vogel, 2014). This relationship suggests that WM may be a core cognitive ability that underlies—and constrains—our ability to process information across cognitive domains. Thus, understanding the WM mechanism could provide important insight into general cognitive function.

1.3 From WM to visual WM

Since Baddeley proposed the multicomponent model (Baddeley & Hitch, 1974) by using verbal stimulus as memory material, researchers have done a lot of research on the processing and storing of verbal information, particularly the mechanism of the phonological loop or verbal WM (Baddeley, 2012), which was dominated by verbal paradigms. In the broader WM literature, a significant amount of research has focused on characterising memory limits based on how quickly information can be refreshed (Baddeley, 1986) or the rate at which information decays (Baddeley & Scott, 1971). The most common paradigm for investigating WM is the digit span task, in which participants were asked to repeat a series of numbers (Engle, Tuholski, Laughlin, & Conway, 1999). Although there are many studies on visuo-spatial WM (Baddeley, 1992; Darling, Della Sala, & Logie, 2007; Darling, Sala, & Logie, 2009; Della Sala, Logie, Beschin, & Denis, 2004; Deyzac, Logie, & Denis, 2006; Garden, Cornoldi, & Logie, 2002; Logie, 2003; Postle, Idzikowski, Sala, Logie, & Baddeley, 2006; Rudkin, Pearson,

& Logie, 2007), the study of visual working memory (VWM), specifically for visual feature information, did not increase dramatically until 20 years ago (Cowan, 2001; Luck & Vogel, 1997). At present, many VWM studies show that information regarding visual objects, visual locations and visual actions are stored in different spaces (Awh & Jonides, 2001; Courtney, Ungerleider, Keil, & Haxby, 1996; Wood, 2007). The VWM discussed in this dissertation refers only to visual object working memory, which could also be termed visual short-term memory (VSTM).

In the 1970s, by using a detection paradigm with a matrix featuring black and white random points as materials, Phillips and his colleague conducted a series of studies on VSTM (W. A. Phillips, 1974; W. A. Phillips & Christie, 1977). However, these studies used the matrix as a material that could cause potential interference with the chunking strategy because of the spatial configuration of the random points. This made it impossible for researchers to correctly estimate the capacity of VWM and correctly describe its processing mechanism (Vogel, Woodman, & Luck, 2001). Luck and Vogel (1997) modified Phillips' paradigm and devoted extensive attention to VWM studies. Participants must report whether the target object is the same as or different from the object previously occupying that location (Jiang, Makovski, Shim, & Brockmole, 2009; Luck & Vogel, 1997). Accuracy in reporting the presence or absence of a change is used to estimate VWM capacity (more details can be found in 1.4.1). Due to the extremely important role of VWM in individuals' advanced cognitive activities, it has attracted the attention of researchers in recent decades and has rapidly become the focus of research in many fields.

VWM is the system enabling one to actively maintain visual information to meet the needs of an ongoing task. It allows individuals to store visual input information from a complex outside environment and provides storage space as an information buffer platform to help integrate information into a continuous visual experience. Recent advances in VWM models have been driven by a focus on the content of WM representations rather than how many individual items can be stored. Most research on VWM has diverged from Baddeley's WM model and developed different theories to explain VWM (Bays & Husain, 2008; Cowan, 2001; van den Berg, Shin, Chou, George, & Ma, 2012; Vogel et al., 2001; Wilken & Ma, 2004; Zhang & Luck, 2008). Whether VWM is best characterized as an information-limited system (Alvarez & Cavanagh, 2004; Wilken & Ma, 2004) or whether it has a predetermined and fixed item limit (Luck & Vogel, 1997; Zhang & Luck, 2008) is an active topic of debate in the field.

It is generally accepted that the capacity of VWM is quite limited and there is a stable individual difference in VWM capacity. There is also a positive correlation between VWM capacity and measures of higher cognitive function. VWM capacity could account for 43% of fluid intelligence (Fukuda et al., 2010). A growing body of literature recognises the importance of VWM mechanisms.

In early studies of VWM, researchers defined VWM capacity as the maximum number of items that an individual can store in VWM (Luck & Vogel, 1997). However, in recent studies, researchers began to focus on the precision of

VWM representations. VWM precision is based on the degree of correspondence between the target items and VWM representations (Wilken & Ma, 2004). VWM capacity should be characterised based on the quantity limitation of VWM and the precision with which each representation can be stored in VWM. This type of memory could be considered analogous to random access memory (RAM), which is used by computers for images. Like the RAM system, which has a fixed upper limit of storage, VWM has a limited capacity. In addition, VWM precision involves the resolution of each stored image.

1.4 Paradigms and measures of VWM

1.4.1 Change detection task

The change detection task is widely used in VWM studies. In one example of the colour change detection task, each trial includes four sessions: the fixation point, memory array, blank interval and test array. Participants are asked to memorize a few colours in the memory array and detect any changes in the test array. Each trial begins with a fixation cross that is present in the centre of the screen for 200 ms, followed by a memory array of a few colours (100–500 ms), a blank period (900–2500 ms) and finally a test array (until the participant responds). The participant is tasked with indicating whether the colours of test array were identical to those of the memory array or colour changes in the test array compare to the memory array. There are two versions of the change detection task: the single-probed recognition and whole-display recognition tasks (Figure 2). In the former, one probe colour is presented at a location of a memory item. This probe colour is either the original colour in the memory array or a novel colour. Participants must recognise the probe colour. In the latter task, a full set of colours is presented during the test array. Either the set used in the test array is the same as the original set in the memory array or one colour is novel. The two tasks differ in that individuals participating in the single-probed recognition task know which item may change and so need to evaluate the status of only a single probe item, while individuals participating in the whole-display recognition task do not know which item may change and so need to evaluate the status of each probe item (Wheeler & Treisman, 2002).

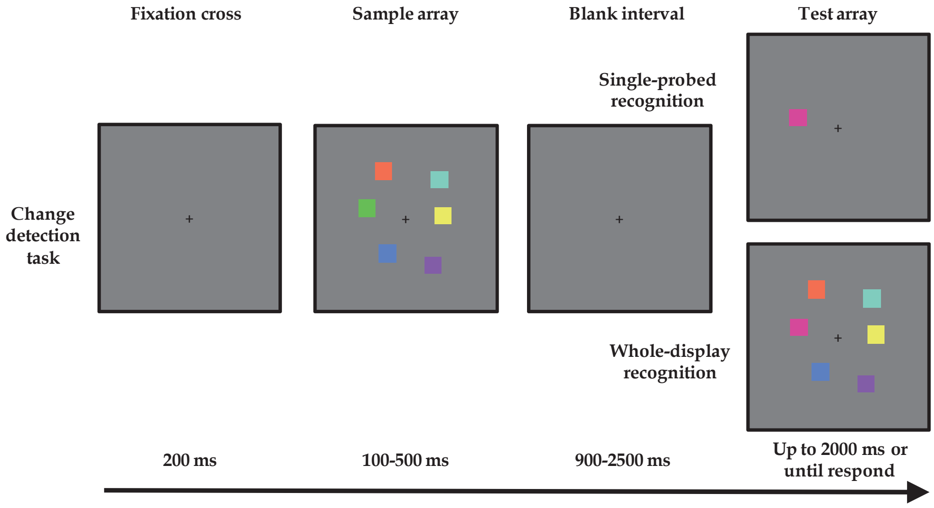

FIGURE 2 The structure of two versions of change detection tasks.

For the single-probed recognition change detection task the number of items stored in VWM can be calculated by using the formula proposed by Cowan (2001):

$$K_C = N \times (H - F)$$

For the whole-display recognition change detection task, the number of items stored in VWM can be calculated by using the formula proposed by Pashler (1988):

$$K_p = N \times (\frac{H-F}{1-F}),$$

where K_c and K_p represent the number of items stored in VWM, N represents the set size of the memory array, H represents the hit rate and F represents the false alarm rate (Pashler, 1988; Cowan, 2001). Using these methods, the change detection task becomes a good paradigm for measuring individual VWM quantity limitation (also called individual VWM capacity).

1.4.2 Recall task

Although most VWM studies ask participants to judge whether memory items have changed to measure VWM performance, a new VWM task was developed using a different testing procedure. Wilken and Ma (2004) asked participants to recall a memory colour by choosing a colour on the colour wheel. Known as the recall task, this was widely used in later studies of VWM precision. In an example of the colour recall task, each trial includes four different sessions: the fixation point, memory array, blank interval and recall array. Participants are asked to memorize a few colours in the memory array and report the colour of one target in the memory array. Each trial begins with a fixation that is present in the centre of the screen for 200 ms, followed by a memory array of a few colours (100–500 ms), a blank period (900–2500 ms) and finally a recall array (until the participant responds). The participant is tasked with choosing the colour of the cued item from a colour wheel (Figure 3).

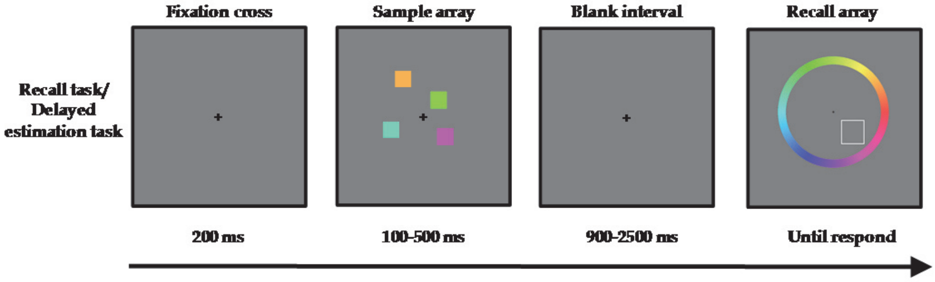

FIGURE 3 The structure of the recall task.

By using this task, researchers have developed different models to fit the results of this task so that the VWM precision (quality) and number (quantity) indices can be measured separately. In each trial, a difference value, also called the offset, between the memory target object and report object is calculated. Zhang and Luck (2008) proposed a standard mixture model to explain the offset results, which are comprised of the contributions of two different components: random responses and noisy internal memory. In the trials for random responses, participants failed to store the target representation in VWM and so had to simply guess and report the results conforming to a uniform distribution. The trials related to the noisy internal memory feature a noisy VWM representation of the target, so they report results conforming to a von Mises distribution. The standard mixture model of the colour recall task can be described as follows:

$$p(\hat{\theta}) = (1-\gamma)\Phi_{\sigma}(\hat{\theta}-\theta) + \gamma\frac{1}{2\pi},$$

where θ represents the value of the target item, $\hat{\theta}$ represents the reported value, γ represents the percentage of trials associated with the random responses and Φ_{σ} represents the von Mises distribution. The mean value of the von Mises distribution is zero and the standard deviation is σ.

Later, Bays et al. (2009) proposed a swap model with an additional component, non-target responses, to explain the offset results. In addition to the two components of the standard mixture model, they suggested that there is a certain possibility participants will confuse the representation of memory, making a mistake and responding to the non-target representation as the target. In the trials with non-target responses, participants report the results conforming to a von Mises distribution centred on the value of one of the non-target items. The swap model of the colour recall task can be described as follows:

$$p(\hat{\theta}) = (1-\gamma-\beta)\Phi_{\sigma}(\hat{\theta}-\theta) + \gamma\frac{1}{2\pi} + \beta\frac{1}{m}\sum_{\mathrm{i}}^{m}\Phi_{\sigma}(\hat{\theta}-\theta_{i}^{*}),$$

where β represents the percentage of trials with non-target responses.

By using maximum likelihood estimation, both the standard mixture model and swap model have parameters to quantify the number of stored items and VWM precision based on the recall response in the recall task. For example, the VWM number index guess rate (P_g) and precision index (SD) can be determined using the standard mixture model. The VWM number index, guess rate (P_{gs}), non-target reported rate (P_{bs}) and precision index (SD_s) can be obtained using the swap model. This approach has enabled VWM research to gradually expand from exploring VWM in general to exploring VWM precision (Bays et al., 2009; Zhang & Luck, 2008, 2009, 2011). It has also made it possible to further explore the trade-off between VWM number and VWM precision in the present research.

1.5 Event-related potentials component of VWM

Early behavioural studies of VWM often used a change detection task to measure VWM performance (Luck & Vogel, 1997). The change detection task requires participants to judge whether an object in the test array has changed. This can cause a potential problem: during the change detection task, participants need to complete a variety of cognitive processes, including a decision-making process. These processes, which are not related to VWM, may contaminate the behavioural results. Therefore, researchers could not observe pure VWM performance based only on the behavioural results.

To track VWM maintenance and avoid potential contamination, one can track the activity of event-related potentials (ERPs) during the retention period of the change detection task. Using the ERP technique, Vogel and Machizawa (2004) developed a bilateral change detection task to identify the ERP component related to VWM maintenance. A bilateral change detection task requires participants to memorize the attended-side stimuli so the researchers can observe the ERP difference between the attended and non-attended sides. Vogel and Machizawa (2004) found a negative slow difference wave that persisted during the VWM maintenance phase after the memory stimuli disappeared. Importantly, the amplitude of this difference wave enhanced with an increase in the number of objects stored in VWM, reaching an asymptote when the number of items stored in VWM reached individuals' VWM quantity limitation. They named this negative slow difference wave the contralateral delay activity (CDA) (Vogel and Machizawa, 2004). At present, a large number of studies have claimed that CDA is an ERP marker of the number of items stored in VWM (McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005).

1.6 VWM theory

1.6.1 Nature of VWM resource

The literature on VWM debates the relative importance of the nature of VWM resources. Two broad theories regarding the nature of VWM resources have been proposed: a discrete resource theory and a continuous resource theory.

In the early discrete resource theory, the most influential model is the classic slot model, which suggests that VWM has a limited number of memory 'slots'. Each slot can store a single object with a fixed precision (Cowan, 2001; Luck & Vogel, 1997; Vogel et al., 2001). When all the slots are occupied, an individual cannot further store any new visual information in VWM. In addition, as the precision of each VWM representation is fixed, the number of VWM representations does not affect (or only slightly affects) the precision of each representation. Later, a new version of the discrete resource theory, called the slots + averaging model, was proposed. This model suggests that individuals can use multiple slots to represent one object at the same time if the number of items that must be memorized is below the individual's VWM quantity limitation. When this occurs, the VWM representation is remembered more precisely (Zhang & Luck, 2008). The discrete resource theory has been supported by a large number of studies (Barton, Ester, & Awh, 2009; Donkin, Nosofsky, Gold, & Shiffrin, 2013; Rouder et al., 2008; Zhang & Luck, 2011).

The continuous resource theory suggests that VWM units are not discrete slots but should be regarded as continuous resources. In addition, it proposes that an individual's VWM does not have a fixed quantity limitation. Rather, VWM contains a pool of resources that can be flexibly allocated to perform different tasks. When a VWM representation is allocated more resources, the precision of that representation will be higher (Bays et al., 2009; Bays & Husain, 2008; Bays, Wu, & Husain, 2011; Huang, 2010; Wilken & Ma, 2004). Recently, the variable precision model, which is based on the continuous resource theory, was proposed. This model suggests that each representation is allocated different resources in each trial, which causes the VWM precision of each representation to vary randomly between trials (Fougnie, Suchow, & Alvarez, 2012; van den Berg et al., 2012). However, the debate between the discrete resource theory and continuous resource theory is still unresolved (Balaban & Luria, 2015; Franconeri, Alvarez, & Cavanagh, 2013; Luck & Vogel, 2013; Vogel & Machizawa, 2004).

1.6.2 Quantity limitation

Individuals' limited memory capacity limits the bandwidth they can use to process information at the same time, which determines the efficiency limitation of many individuals' advanced cognitive processing. In early studies of short-term memory, researchers have that the capacity of short-term memory is limited (G. A. Miller, 1956). As mentioned above, G. A. Miller (1956) proposed that the average individual's short-term memory can manage about 7 ±2 objects. Half a century later, Cowan (2001) challenged this assumption based on the belief that G. A. Miller (1956) overestimated the maximum number of short-term memory, and with much experimental evidence, concluded that the average short-term memory span of a human being is around 4 objects. Further, the evidence presented in G. A. Miller's (1956) study failed to fully separate each item from different objects. That is, some items may have formed a chunk without being identified by the researchers. Luck and Vogel's (1997) landmark study investigated individuals' VWM quantity limitation by asking participants to memorise colour (or orientation) arrays during a short exposure. Their results support that VWM is limited to around three to four simple visual objects (visual chunks). Since this study, the quantity limitation of VWM has become a hot topic in the field of memory.

1.6.3 Trade-off between VWM number and precision

Alvarez and Cavanagh (2004) proposed that because VWM has a fixed total information limit, there is a trade-off between the number of representations stored in VWM and the precision of each representation. By asking participants to memorise different types of objects ranging from low information load to high information load (colours, letters, Snodgrass line drawings, Chinese characters, random polygons, shaded cubes), they manipulated the information of each object that needs to be memorised. Their results indicated that the quantity limitation of VWM depends on the complexity of object to be memorised. Participants needed to use more precise VWM to store more complex objects and detect whether those objects changed in the change detection task. However, the higher the precision of each stored object, the fewer objects can be stored in VWM. Their results are line with the idea that there is a negative correlation between VWM number and VWM precision, and they argue that the VWM system can store a limited amount of visual information. That is, as in the above example of a RAM system, in order to ensure that the total processing information does not exceed the upper storage limit of the RAM system, when there are more stored images, the resolution of these images will be lower. This leads to the existence of a trade-off between the number and resolution of images. The total storage information of the RAM system should be equal to the number of stored images multiplied by the average resolution of each stored image.

Wilken and Ma (2004) also demonstrated the trade-off between VWM number and precision using a recall task to directly measure VWM precision. They found that VWM precision decreased monotonously with an increase in memory objects. These studies suggest that the VWM system does not store a fixed number of representations with fixed precision (Alvarez & Cavanagh, 2004; Wilken & Ma, 2004). In contrast, the precision of representations in the VWM system depends on limited resources that are shared among representations. Thus, a single object can be represented with high VWM precision, but several objects can be represented only with lower precision.

Several behavioural and ERP studies have investigated the trade-off between VWM number and precision (Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Gao et al., 2009; Luria, Sessa, Gotler, Jolicoeur, & Dell'Acqua, 2010; Zhang & Luck, 2008).

1.7 Summary of the present research

In early studies, memory processes were often believed to exist in three different stages: registration, retention and retrieval (Arnold, 2013). Similarly, VWM includes various mechanisms: encoding, consolidation, maintenance and retrieval of information. When visual stimuli appear, individuals need to encode the stimuli and consolidate them into VWM for creating representations. When the stimuli disappear, individuals need to maintain these representations. When a subsequent task needs to use this information, individuals need to retrieve the information from representations. Because the retrieval process often overlaps advanced processes such as the decision making process in the response stage in order to avoid interference from these processes, the current research focused mainly on consolidation and maintenance.

This research included 15 experiments (two experiments for Study I; one experiment for Study II; three experiments for Study III; two experiments for Study IV; three experiments for Study V; four experiments for Study VI). In total, 357 healthy adults participated in the research (N = 42, N = 18, N = 146, N = 52, N = 47, and N = 92 in Studies I–VI, respectively). Three different paradigms were used: the bilateral version of the change detection task for measuring CDA (Studies I and II), the recall task for measuring VWM precision (Studies III, IV, V and VI) and the single-probed recognition version of the change detection task for measuring VWM capacity (Study IV). Ongoing debates related to the present research concerning the consolidation and maintenance processes are listed in the following sections.

1.7.1 Manner of VWM consolidation

In studies of VWM consolidation, the manner of consolidation of items in VWM has been a controversial topic. Two manners have been proposed: parallel and serial consolidation (J. R. Miller, Becker, & Liu, 2014; Rideaux, Apthorp, & Edwards, 2015). Parallel consolidation refers to simultaneous consolidation of multiple items in VWM, while serial consolidation means that individuals can only consolidate one item at a time. One series of studies suggested that the manner of consolidation of VWM depends on the stimulus feature. For simple stimuli such as colours, individuals can consolidate colours in VWM in a limited-capacity parallel manner (two items at a time), but for complex stimuli such as orientations, individuals can only consolidate orientations in a serial manner (Becker, J. R. Miller, & Liu, 2013; Liu & Becker, 2013; Mance, Becker, & Liu, 2012; J. R. Miller, Becker, & Liu, 2014). However, new evidence suggests that the orientations can be consolidated in a limited-capacity parallel manner (Rideaux, Apthorp, & Edwards, 2015; Rideaux & Edwards, 2016). Thus, there is still controversy about whether the manner of consolidation is determined by the type of stimulus feature.

The aim of Study I was to use the ERP technique to examine whether the manner of consolidation depends on the type of information. Using the CDA component, tests were performed to determine whether the colours and orientations are both consolidated in a parallel manner or whether the orientations are consolidated in a serial manner but the colours are consolidated in a parallel manner. The main results of Study I were reported in Article I.

1.7.2 Relationship between VWM quantity limitation and precision for different materials

Lots of studies have investigated the relationship between VWM number and precision. The evidence has supported the decline in the VWM precision of each representation as the number of stored items increases. However, it is not yet certain whether or not the VWM quantity limitation is affected by the variation in VWM precision required by different tasks. By using orientation stimuli, two ERP studies showed that using a high-precision way to memorise orientations can store fewer items than a low-precision method (Gao, Yin, Xu, Shui, & Shen, 2011; Machizawa, Goh, & Driver, 2012). This suggests that, for the orientation stimuli, the VWM quantity limitation decreases with the increase of the VWM precision requirements. Nevertheless, the similar inverse relation between the VWM quantity limitation and precision requirement was not found in the ERP study using colour as stimuli (Ikkai, McCollough, & Vogel, 2010). Therefore, there is still an argument regarding whether the VWM quantity limitation of colour stimuli is affected by VWM precision requirements.

The aim of Study II was to use the ERP technique to examine the relationship between the VWM quantity limitation and VWM precision for colour feature. Using the CDA component, tests were conducted to determine whether the VWM quantity limitation decreases with an increase in the VWM precision of the task requirement. The main results of Study II were reported in Article II.

1.7.3 Manner of trade-off between VWM quantity and precision

There has been contradictory evidence regarding the manner of the trade-off between VWM quantity and precision. Some studies suggested that participants could not voluntarily trade off between VWM quantity and precision depending on a task’s requirements (Zhang & Luck, 2008). In addition, the VWM precision of each representation depends only on the number of representations stored in VWM. Several experiments used similar paradigms but obtained opposite results, finding that participants could voluntarily trade off between VWM quantity and precision based on the task requirements (Machizawa et al., 2012). To my knowledge, no satisfactory explanations have been offered to reconcile these discrepant findings, and thus this topic is still controversial.

In Study III, the aim was to test whether the memory set size and exposure duration of a memory array affect voluntary trade-off between VWM precision and quantity. The main results of Study III were reported in Article III.

Similar to Study III, the goal of Study IV was to explore other factors that may have had an impact on voluntary trade-off between VWM precision and quantity. The influence of individuals' VWM quantity limitation for simple items on the trade-off was tested in Study IV. The main results of this study were reported in Article IV.

1.7.4 Impact of bilateral field advantage on VWM

Previous studies have shown that the allocation of VWM resources is influenced by external factors such as the location of presentation of the memory array. By using a change detection task, Delvenne (2005) found that VWM performance was better when a memory array was presented in bilateral visual hemifields than when a memory array was presented in a unilateral visual hemifield. This phenomenon was called the bilateral field advantage (BFA) of VWM, and it may indicate that VWM resource allocation was more effective or participants had more VWM resources when a memory array was presented in bilateral visual hemifields. That is, the location of presentation of a memory array affects VWM resource allocation. However, the change detection task could indicate only VWM performance and could not index detailed information, such as VWM precision, which is related to VWM resource allocation. So, the evidence obtained from change detection tasks is not sufficient to disclose the impact of presenting memory array in bilateral visual hemifields on VWM resource allocation.

The aim of Study V was to explore the effect of BFA on VWM resource allocation. The main results of this study were reported in Article V.

1.7.5 Impact of internal attention on VWM resource allocation

Since VWM and attention share similar neural mechanisms (Ku, 2018), the interaction of attention and VWM has always been an important topic in the field of memory (Underwood, 2013). Many studies have suggested that the content of VWM unconsciously directs attention to targets that have features similar to the VWM content (Downing, 2000; Lu et al., 2017; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). Based on the classification proposed by Chun, Golomb and Turk-Browne (2011), the attention affected by VWM content can be considered external attention.

Recently, the influence of internal attention on VWM has been widely studied. This term refers to the attention that an individual uses to select and operate internal memory representations and is contrasted with external attention, which refers to the selection of the external items. Researchers have invented a retro-cue task to investigate the role of internal attention on VWM

(Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003). This task is similar to the general VWM task, except that after the memory array disappears, the participant receives a retro-cue representing one VWM representation of a spatial location. Researchers found that VWM performance was significantly better in the valid retro-cue condition than in the invalid retro-cue condition. These results suggest that even if the memory stimuli have disappeared, individuals can still allocate VWM resources to gain an advantage regarding the target representation by using internal attention. Since then, the retro-cue task has been widely used in studies examining the impact of internal attention on VWM (see a review Souza & Oberauer, 2016). Although the role of internal attention to VWM has been explained by different hypotheses (Kuo, Yeh, Chen, & D'Esposito, 2011; Makovski & Pertzov, 2015; Vandenbroucke, Sligte, de Vries, Cohen, & Lamme, 2015; Williams, Hong, Kang, Carlisle, & Woodman, 2013), these studies have only focused on the influence of object-based internal attention on VWM performance, no studies have investigated the impact of dimension-based internal attention on VWM resource allocation.

The aim of Study VI was to explore the effect of dimension-based internal attention on VWM resource allocation, that is, to examine whether dimension-based internal attention can dynamically affect weight dimension-specific representations within multi-dimensional objects stored in VWM. The main results of Study VI are reported in Article VI.

2 STUDY I: MANNER OF VWM CONSOLIDATION FOR DIFFERENT MATERIALS

2.1 Introduction

In the last two decades, the consolidation phase of VWM has been widely studied. Studies have suggested that the individual is limited not only by the quantity of items that can be stored in VWM but also by the bandwidth of VWM consolidation (Jolicoeur & Dell'Acqua, 1998; Stevanovski & Jolicoeur, 2011; Vogel, Woodman, & Luck, 2006; West, Pun, Pratt, & Ferber, 2010; Zhang & Luck, 2008). Two different manners of VWM consolidation have been proposed based on the limitations of VWM consolidation, the serial consolidation process and the limited-capacity paralleled consolidation process. For example, Huang and his colleagues used the Boolean map theory to predict that an individual can consolidate only one item at a time (Huang, 2010; Huang & Pashler, 2007; Huang, Treisman, & Pashler, 2007). Thus, they proposed a serial consolidation process. However, Mance et al. (2012) provided new evidence indicating that it is possible to consolidate colours in a parallel manner, but the parallel consolidation bandwidth is limited to two items. Therefore, they proposed a limited-capacity paralleled consolidation process.

In a series of follow-up studies, researchers found that these two manners of VWM consolidation may depend on the features of memory targets (Becker et al., 2013; Liu & Becker, 2013; Mance et al., 2012; J. R. Miller et al., 2014). These studies concluded that individuals can only consolidate orientation materials in a strictly serial way but can consolidate colour materials in a parallel way when the number of consolidated colours is no more than two. Nevertheless, two behavioural studies have challenged this conclusion regarding the manner of VWM consolidation of the orientation materials (Rideaux et al., 2015; Rideaux & Edwards, 2016), proposing that orientations can be also consolidated in a limited-capacity parallel manner.

Since the previously mentioned studies about the manner of VWM consolidation are all behavioural studies and there are many differences between the studies, it is difficult to obtain reliable conclusions. In previous behavioural studies, the consolidation of a target was investigated by presenting two targets either sequentially or simultaneously (Becker et al., 2013; Liu & Becker, 2013; Mance et al., 2012; J. R. Miller et al., 2014). Although the simultaneous versus sequential paradigm seems to be a powerful method for investigating consolidation in VWM, interpretation of the results depends on the set of assumptions one makes about the task. Thus, it seems that a converging method, particularly one that does not require comparisons across conditions with different numbers of stimuli for each display, would help clarify that the results are influenced by consolidation mechanisms rather than other strategic or low-level perceptual differences that may differ across simultaneous and sequential presentation conditions. CDA was used to examine the VWM consolidation processes. Importantly, this method does not require one to compare a simultaneous condition to a sequential one, thereby eliminating the interpretational issues raised above. In addition, due to the potential issues of VWM behavioural studies mentioned above in the general introduction, using the ERP technique could also help clarify the conclusion regarding the manner of VWM consolidation. Therefore, in Study I, CDA was used to determine how many colours or orientations can be consolidated into VWM when the exposure duration of memory array is sufficient to conduct consolidation only one time. The memory set size and exposure duration of the memory array were manipulated to investigate the bandwidth of VWM consolidation for colour materials (Experiment 1) and orientation materials (Experiment 2).

2.2 Experiment 1 - Bandwidth of consolidation in colour feature

2.2.1 Methods

Participants

A total of 20 participants (11 females) were recruited from the participant pool at Liaoning Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Liaoning Normal University.

Stimuli

Participants viewed the display at a distance of 60 cm, and the stimuli were presented on a 21-inch LCD monitor (800×600 pixels) in a dark room. The memory array of six distinct colour stimuli ($0.65^{o}\times0.65^{o}$) was randomly displayed around a central fixation cross. The mask ($0.65^{o}\times0.65^{o}$) featured a 6×6 multicolour checkerboard pattern comprising six different colours as the sample array. The colour of each square was randomly assigned to each mask.

Procedure

The experiment took place over two sessions. Participants first completed a pre-task to measure the minimum exposure duration required to consolidate a single coloured item. In this session, each trial began with 200 ms arrow cues above and below fixation, followed by a variable delay that ranged from 100 to 200 ms. Then, a single-colour square was presented and masked in a random location within each hemifield (Figure 4). Eight durations were used for the memory array: 7 ms, 14 ms, 28 ms, 56 ms, 98 ms, 154 ms, 224 ms and 308 ms. Participants needed to indicate whether the colour in the cued hemifield of the test array was identical to the one in memory array. Each duration condition had 32 trials, resulting in a total of 256 trials. By fitting the data with a Weibull function (Wichmann & Hill, 2001), the exposure duration that yielded 80% accuracy was calculated and used in the main task.

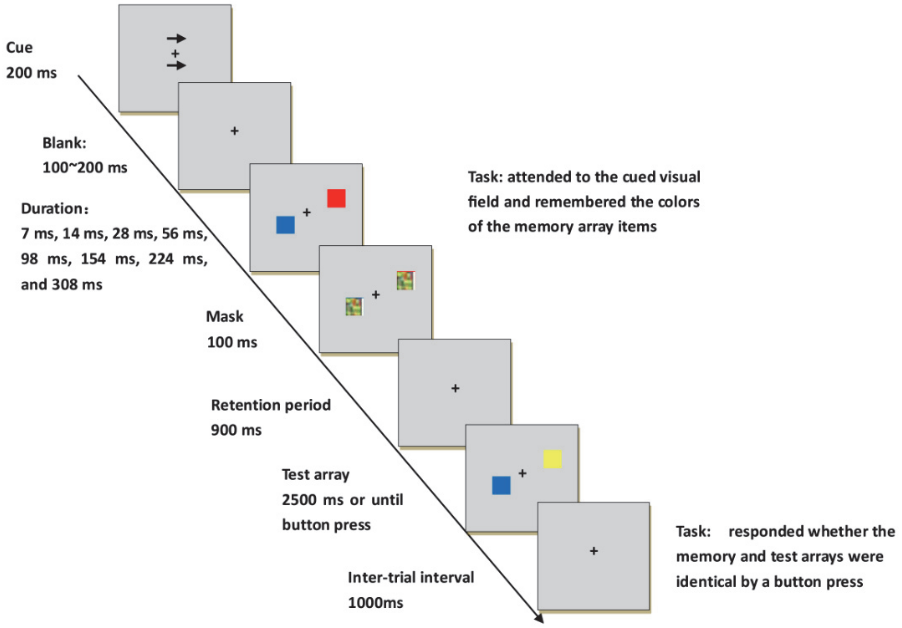

FIGURE 4 Trial schematic of the pre-task applied in Experiment 1.

After the first session, participants completed the main task with electroencephalographic (EEG) data recordings. In this session, each trial began with 200 ms arrow cues above and below fixation, followed by a variable delay that ranged from 100 to 200 ms. Then, the memory array was presented for 300 ms or the exposure duration associated with 80% accuracy (the minimum time, which was determined by the threshold procedure described previously). After the memory array disappeared, masks were immediately presented for 100 ms, followed by a 900 ms blank period and a 2500 ms test array (Figure 5). Participants needed to memorise the colours in the cued hemifield and indicate whether the test array of the cued hemifield was identical to the memory array of the cued hemifield. Accuracy was stressed in this experiment rather than response speed.

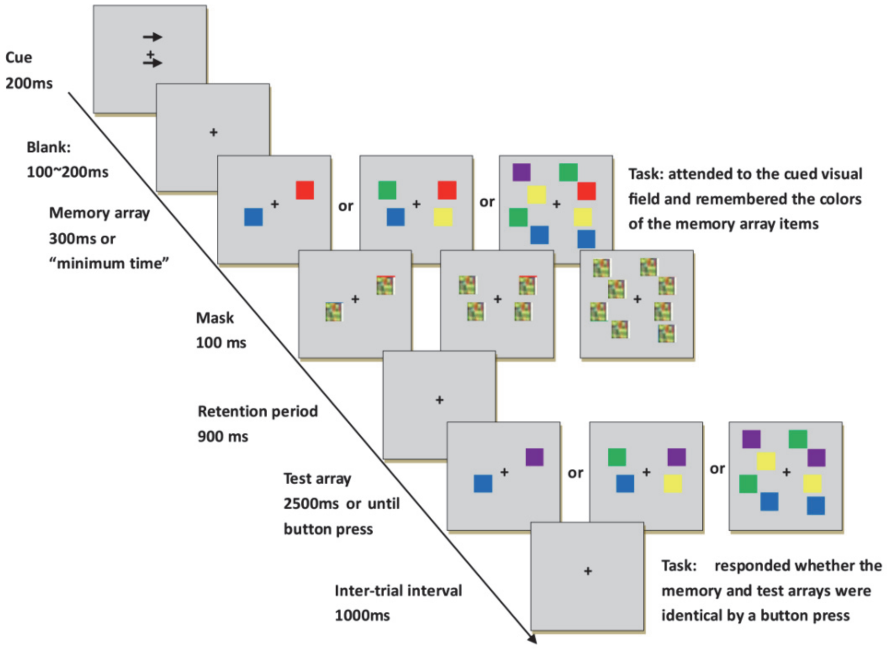

FIGURE 5 Trial schematic of the main task applied in Experiment 1.

In the main task, three levels of set size (one, two and four) and two levels of exposure durations (300 ms and minimum time) were varied. Six conditions were thus intermixed within blocks. Before the experiment started, participants practiced for at least 12 trials to ensure that the participants understood the procedures. Each condition had 120 trials per condition, resulting in a total of 720 trials.

EEG recording and analyses

By using a QuickAmp amplifier at a sampling rate of 500 Hz with a 100 Hz low-pass, EEG data was recorded from an elastic cap with 64 tin electrodes. Two electrodes were used to register vertical electrooculograms (VEOGs) and horizontal electrooculograms (HEOGs): one placed below the left eye (VEOG) and the other one placed next to the right eye (HEOG). The impedance of each electrode was maintained below 5kΩ to ensure signal quality. Channels were referenced online to the CZ electrode and re-referenced offline to the average of the right and left mastoids. Trials with artefacts (±75 V at all channels) were rejected. The remaining trials were segmented into 1100 ms epochs (from 100 ms before to 1000 ms after the onset of the memory array).

The CDA was measured at the posterior parietal (P7/P8 and PO7/ PO8) as the difference in mean amplitude between ipsilateral and contralateral waveforms. A 600-1000 ms measurement window after the onset of memory array was used to calculate the mean amplitude.

2.2.2 Results and discussion

Behavioural results

The mean minimum time for participants was 60 ± 32 ms (21–147 ms). A two-way ANOVA with set size (one vs. two vs. four) and exposure duration (minimum time vs. 300 ms) was conducted to determine accuracy. This revealed the significant main effect of set size [$F(2,38) = 283.99$, $p < .001$] and exposure duration [$F(1,19) = 93.89$, $p < .001$]. The interaction between set size and exposure duration was also significant [$F(2,38) = 5.71$, $p < .01$].

Planned comparisons were conducted and showed that, in the minimum time condition, the accuracy of the one-colour condition was higher than that of the two-colour condition [$t(19) = 8.01$, $p < .001$], and the accuracy of the two-colour condition was higher than that of the four-colour condition [$t(19) = 8.86$, $p < .001$]. A similar pattern of results was also found in the 300 ms condition [$t(19) = 4.20$, $p < .001$ for one-colour condition vs. two-colour condition; $t(19) = 14.88$, $p < .001$ for two-colour condition vs. four-colour condition] (Figure 6a). The accuracy decreases monotonously with the increase of set size due to increases in the set size, interference between items and decision noise. Therefore, the behaviour result is not sufficient to discriminate parallel consolidation from serial consolidation.

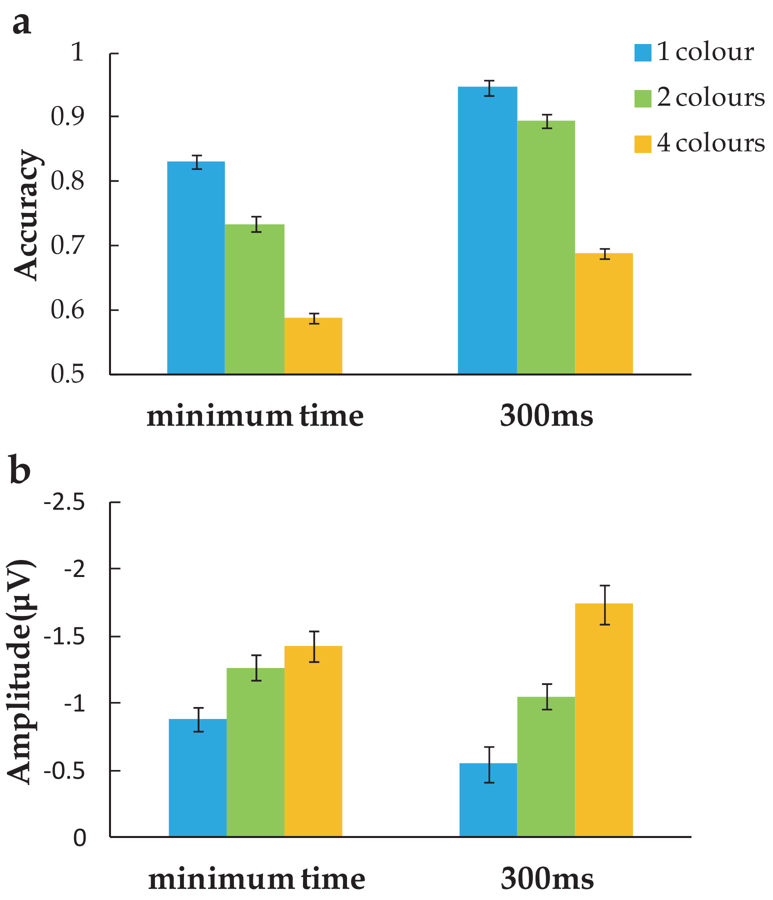

FIGURE 6 The (a) behavioural and (b) CDA amplitude results in Experiment 1. Error bars are standard error of the mean.

ERP results

Figure 7 displays the CDA time-locked to the onset of the memory array for each set size level in different exposure duration conditions. A two-way ANOVA with a given set size (one vs. two vs. four) and exposure duration (minimum time vs. 300 ms) was conducted for CDA amplitude. It revealed the main effect of set size [$F(2,38) = 17.05$, $p < .001$], but exposure duration did not have a significant main effect [$F(1,19) = 0.66$, $p > .05$]. The interaction between set size and exposure duration was significant [$F(2,38) = 5.12$, $p < .05$].

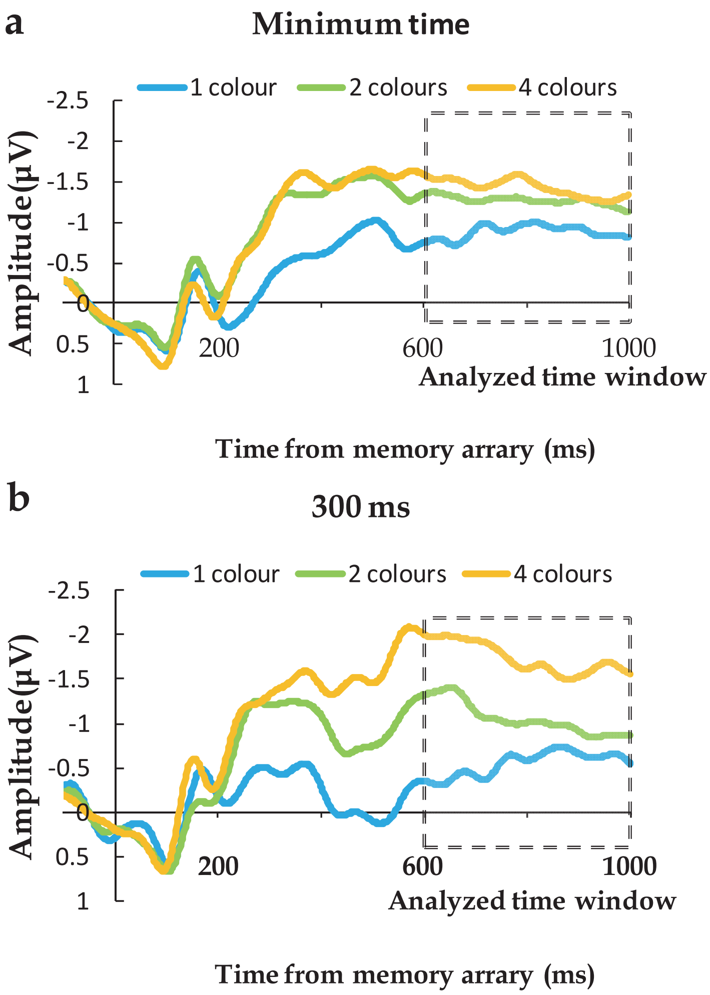

FIGURE 7 Grand-averaged CDA difference waves of the minimum time and 300 ms conditions in Experiment 1. The waves were time-locked to the onset of the memory array.

Planned comparisons were conducted and showed that, in the minimum time condition, the CDA amplitude of the one-colour condition was smaller than that of the two-colour condition [$t(19) = 2.61$, $p < .05$]. However, the CDA amplitude of the two-colour condition was not significantly different from that of the four-colour condition [$t(19) = 1.11$, $p > .05$]. In contrast, in the 300 ms condition, the CDA amplitude of the one-colour condition was smaller than that of the two-colour condition [$t(19) = 3.02$, $p < .01$], and the CDA amplitude of the two-colour condition was smaller than that of the four-colour condition [$t(19) = 3.26$, $p < .01$] (Figure 6b).

The CDA results showed that, in the minimum time condition, participants could only memorise two colours, but in the 300 ms condition, participants could memorise more than two colours. This suggested that participants could consolidate two colour materials at one time. These results are in line with previous studies (Mance et al., 2012; J. R. Miller et al., 2014), which suggested that consolidation of colour materials is a parallel process with a bandwidth of two items. The results of the current study support the hypothesis that colour materials could be consolidated in parallel with a two-item bandwidth and provide evidence that the bandwidth is not due to limitations of an individual's VWM capacity.

2.3 Experiment 2 - Bandwidth of consolidation in orientation feature

In Experiment 2, this method was extended to consolidation of oriented gratings in order to investigate whether the process of consolidating orientation information also occurs in parallel or occurs only serially.

2.3.1 Methods

Participants

A total of 20 participants (12 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Liaoning Normal University.

Stimuli

The apparatus used in Experiment 2 was similar to that used in Experiment 1. In addition, sinusoidal gratings (orientation, 0.9°×0.9°) were used as visual stimuli. The mask ($1^{o}\times1^{o}$) was comprised of pixel noise with random luminance levels.

Procedure

In the pre-task, the procedure of exposure duration was the same as that used in Experiment 1, except the stimuli were orientations (Figure 8).

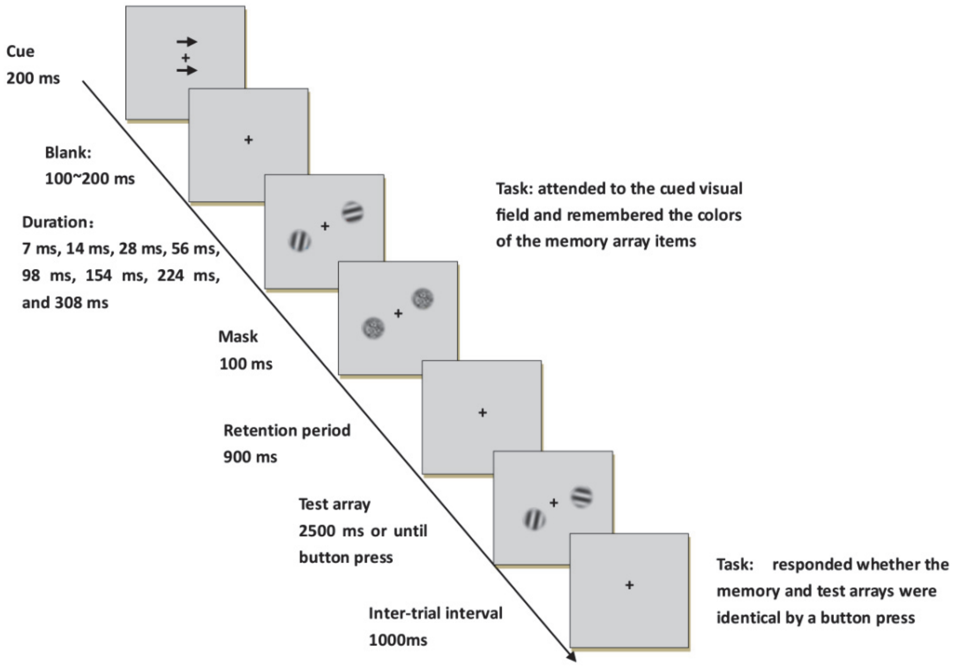

FIGURE 8 Trial schematic of the pre-task in Experiment 2.

The procedure of the main task was also similar to that used in Experiment 1. The memory array consisted of one, two or four different orientations (Figure 9).

Similar to Experiment 1, three levels of set size (one, two and four) and two levels of exposure duration (300 ms and minimum time) were varied. Six conditions were intermixed within blocks. Before the experiment started, participants practiced for at least 12 trials to ensure they understood the procedures. Each condition had 120 trials per condition, for a total of 720 trials.

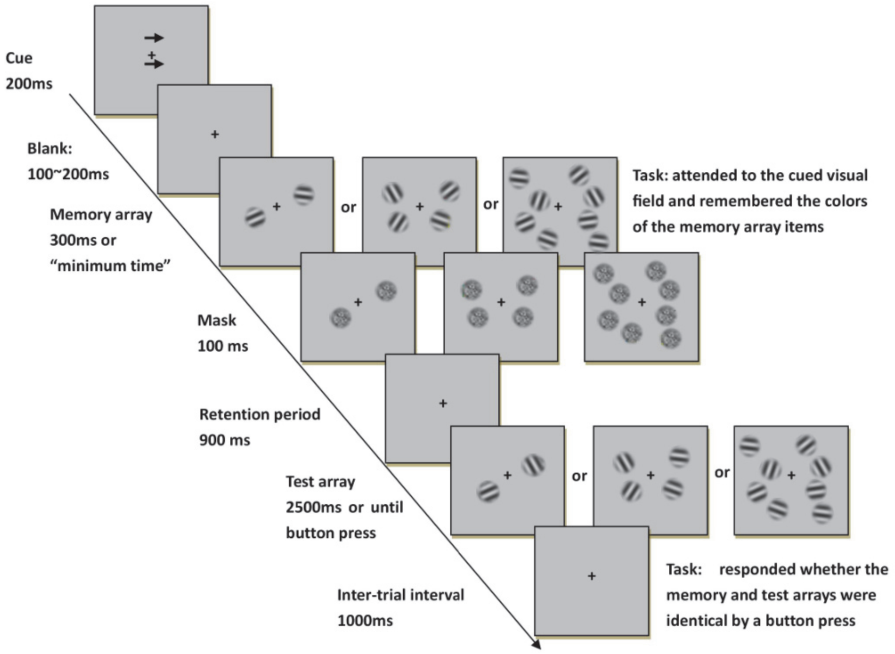

FIGURE 9 Trial schematic of the main task in Experiment 2.

EEG recording and analyses

The procedures for EEG recording and analysis were identical to those used in Experiment 1.

2.3.2 Results and discussion

Behavioural results

The mean minimum time for participants was 57 ± 33 ms (7–119 ms). To determine accuracy, a two-way ANOVA with set size (one vs. two vs. four) and exposure duration (minimum time vs. 300 ms) was conducted. This analysis revealed the significant main effects of set size [$F(2,38) = 385.62$, $p < .001$] and exposure duration [$F(1,19) = 111.06$, $p < .001$]. The interaction between set size and exposure duration was also significant [$F(2,38) = 18.61$, $p < .001$].

Planned comparisons were conducted and showed that, in the minimum time condition, the accuracy of the one-orientation condition was higher than that of the two-orientation condition [$t(19) = 11.92$, $p < .001$]. Additionally, the accuracy of the two-orientation condition was higher than that of the four-orientation condition [$t(19) = 7.93$, $p < .001$]. A similar pattern of results was also found for the 300 ms condition [$t(19) = 6.13$, $p < .001$ for one-orientation condition vs. two-orientation condition; $t(19) = 17.86$, $p < .001$

for two-orientation condition vs. four-orientation condition] (Figure 10a). As in Experiment 1, the accuracy decreases monotonously with increasing set size.

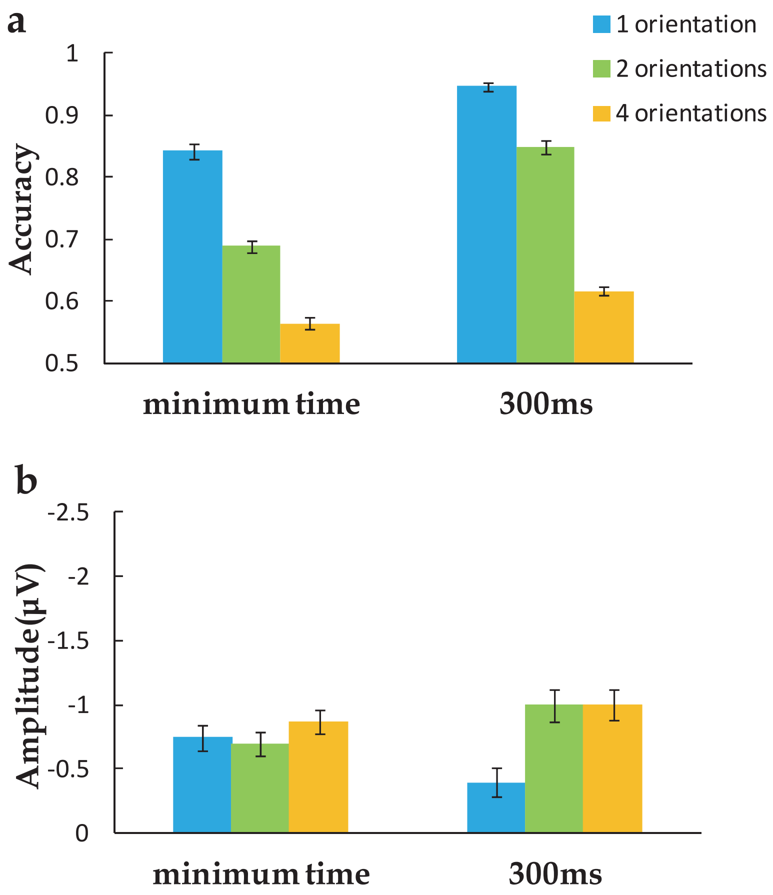

FIGURE 10 The (a) behavioural and (b) CDA amplitude results in Experiment 2. Error bars are standard error of the mean.

ERP results

Figure 11 displays the CDA time-locked to the onset of the memory array for each set size level in different exposure duration conditions. A two-way ANOVA with a given set size (one vs. two vs. four) and exposure duration (minimum time vs. 300 ms) was conducted for CDA amplitude, revealing the significant main effect of set size [$F(2,38) = 5.18$, $p < .01$] but not of exposure duration [$F(1,19) = 0.057$, $p > .05$]. The interaction between the set size and exposure duration was significant [$F(2,38) = 5.12$, $p < .05$].

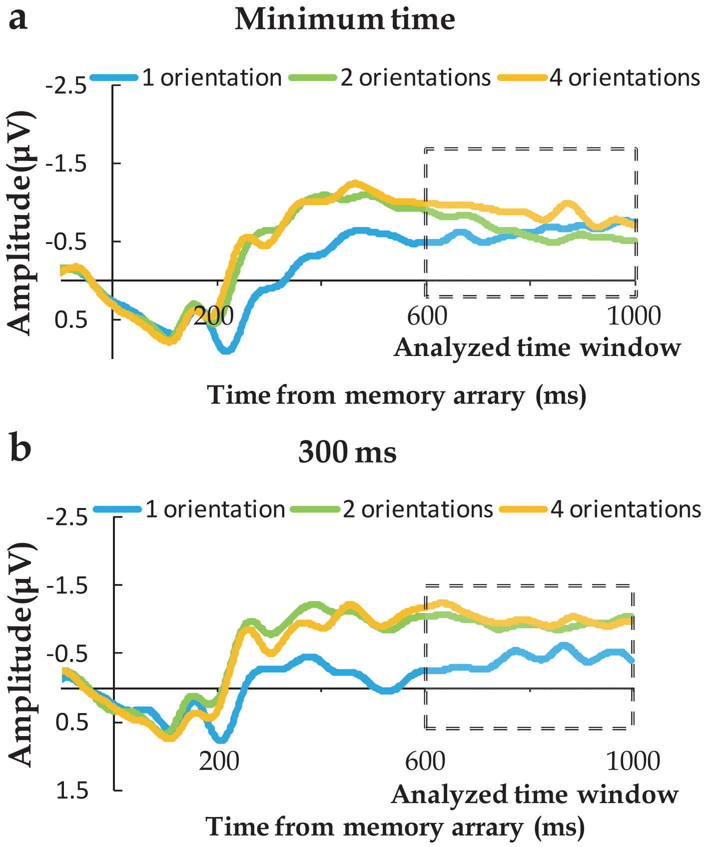

FIGURE 11 Grand-averaged CDA difference waves of the minimum time and 300 ms conditions in Experiment 2. The waves were time-locked to the onset of the memory array.

Planned comparisons were conducted and showed that, in the minimum time condition, the CDA amplitude of the one-orientation condition was not significantly different from that of the two-orientation condition [$t(19) = -0.37$, $p > .05$] and the CDA amplitude of the two-orientation condition was not significantly different from that of the four-orientation condition [$t(19) = 1.16$, $p > .05$]. In contrast, in the 300 ms condition, the CDA amplitude of the one-orientation condition was smaller than that of the two-orientation condition [$t(19) = 3.36$, $p < .01$], but the CDA amplitude of the two-orientation condition was not significantly different from that of the four-orientation condition [$t(19) = 0.03$, $p > .05$] (Figure 10b).

The CDA results showed that, in the minimum time condition, participants could only memorise one orientation. However, in the 300 ms condition, participants could memorise two orientations. These results suggested that, participants could only consolidate orientation materials item-by-item. These results are in line with previous studies (Becker et al., 2013; Liu & Becker, 2013; J. R. Miller et al., 2014), which suggested that consolidation of orientation material is a strictly serial process with a bandwidth of one item. Therefore, these results support the hypothesis that orientation materials can be only consolidated in a serial manner.

2.4 Discussion of Study I

In Study I, the manner of VWM consolidation of colour and orientation materials was tested by measuring accuracy and CDA amplitudes in a change detection task with masks.

If consolidation is a serial process, regardless of the set size of the display, only a single item could be consolidated. Thus, there would be no difference among the CDA amplitudes for different set size (one, two and four) conditions. However, if the consolidation is a parallel process, the CDA amplitude should increase with set size until the bandwidth of consolidation is exhausted. Therefore, the present results suggest that consolidation of colour material is a parallel process with a bandwidth of two items, but participants could consolidate only one orientation material at a time.

Furthermore, the 300 ms duration is used to measure the capacity of VWM storage to ensure that any limits found in the minimum time condition can be attributed to limits in the consolidation process rather than limits in storage capacity. That is, the baseline measure of VWM storage capacity in the settings of Experiments 1 and 2 was determined by the 300 ms exposure condition. In Experiment 1, as the set size increased from one to two and to four, the CDA amplitude increased monotonically for colour stimuli. However, in Experiment 2, for the orientation stimuli, CDA amplitude increased from a set size of one to two but showed no further increase from a set size of two to four. Previous research has established that plateaus of CDA amplitude reflect the maximum number of items held in VWM (Luck & Vogel, 2013). Given the properties of CDA and the results of Experiments 1 and 2, it can be inferred that VWM's capacity for colour is at least three items in Experiment 1 and its capacity for orientation is at least two items in Experiment 2. These results suggest that the observed limits of consolidation are not due to limitation of the storage capacity of VWM.

Given the hypothesis that colour requires fewer consolidation resources than orientation, one might expect that there is a longer minimum threshold for orientation than colour. Largely similar threshold durations were observed in Experiments 1 and 2. However, because consolidation could take the same limited amount of time, regardless of the bandwidth that is consumed, this similarity is not necessarily unexpected. When the number of items exceeds the bandwidth, consolidation processes must be completed multiple times. The consolidation process is prevented by the minimum threshold duration from being completed multiple times, thereby allowing us to measure the number of items that can be accommodated by the bandwidth for different features. Importantly, only the number of iterations that the consolidation process can complete is limited by thresholding and is therefore orthogonal to the bandwidth of a single iteration.

ERP technology features a CDA component to resolve the controversy regarding the manner of VWM consolidation for different materials. The results support that VWM consolidation of colour materials is a parallel process with a bandwidth limited to two colours, while VWM consolidation of orientation materials is a strict serial process. As explained by J. R. Miller et al. (2014), this result may be due to the different encoding processes required for colour and orientation materials; the encoding of colour materials requires less information than the encoding of orientation materials. This causes individuals to have larger bandwidths of consolidation for colour materials than for orientation materials.

The difference in memory materials affects the resource allocation of VWM in the VWM consolidation phase. Further discussion can be found in 8.1. In the next study, I will further explore whether differences in memory materials affect the manner of the trade-off between VWM quantity and precision.

3 STUDY II: VWM RESOURCE ALLOCATION IN CONSOLIDATION FOR COLOR FEATURE

3.1 Introduction

The manner of VWM consolidation of different materials—that is, the manner of allocation of VWM resources in the VWM consolidation phase—was investigated in Study I. Resource allocation in the VWM consolidation phase is reflected in the voluntary trade-off between VWM quantity limitation and VWM precision. A behavioural study suggests that participants could not trade off between the two due to the task requirements for colour stimuli (Zhang & Luck, 2011). On the contrary, previous studies using the CDA component have suggested that, for memorising orientation stimuli, participants have different VWM quantity limitations when different levels of VWM precision are required by different tasks. For example, the VWM quantity limitation for orientation materials becomes lower for tasks that require a high level of VWM precision (Gao et al., 2011; Machizawa et al., 2012). This suggests that, for the orientation stimuli, participants could allocate resources in a voluntary manner. The reason for this may be similar to that in Study I: different encoding methods are used for orientation materials and colour materials, so the manner of the trade-off for colour materials may be different from that for orientation materials.

Although previous studies about the relationship between WM quantity limitation and the required precision for orientation materials used the CDA component to indicate individuals' VWM quantity limitation, the CDA component has not been used in studies using colour materials to test whether participants could trade off voluntarily, which may be a cause of previous contradictions. Thus, Study II used the ERP index to further verify whether the VWM quantity limitation for colour materials is affected by the VWM precision required by certain tasks. By using the CDA component, memory set size and required precision were manipulated in Experiment 3 to test the relationship between the VWM quantity limitation and required precision requirement for colour materials.

3.2 Experiment 3 - Relationship between VWM quantity limitation and precision requirement for colour feature

3.2.1 Methods

Participants

A total of 14 participants (9 females) were recruited from the participant pool at Liaoning Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Liaoning Normal University.

Stimuli

Participants viewed stimuli presented on a 19-inch LED monitor (800×600 pixel) in a dark room at a distance of 70 cm. Six distinct colour stimuli (0.65^{o}×0.65^{o}) of the memory array were chosen randomly. The RGB values for the six colours were green [30,138,18], red [233,0,0], blue [26,49,178], yellow [231,228,66], orange [210,85,7] and purple [156,0,158]. These colours were referred to as the 'original set'. In the high-precision condition, the test colours consisted of six colours similar to original set: green [49, 151,34], red [216,0,0], blue [50,60,192], yellow [216,214,50], orange [226,93,25] and purple [171,31,182]. These colours were referred to as the 'similar set'.

Procedure

Participants completed a change detection task with EEG data recording. Each trial began with 200 ms arrow cues above fixation, followed by a memory array for 100 ms. After the memory array disappeared, there was a 900 ms blank period followed by a 2000 ms test array. Participants needed to memorise the colours in the cued hemifield, and indicated whether the test array of the cued hemifield was identical to the memory array of the cued hemifield. Accuracy, not response speed, was stressed in this experiment. The memory array was kept constant while manipulating the degree of colour between the memory and test array to determine VWM precision. In the low-precision condition, if a colour changed, a new colour square would be randomly selected from the original set without a replacement. In the high-precision condition, a colour change would induce presentation of a corresponding colour from a similar set (Figure 12). Accuracy, not response speed, was stressed in this experiment.

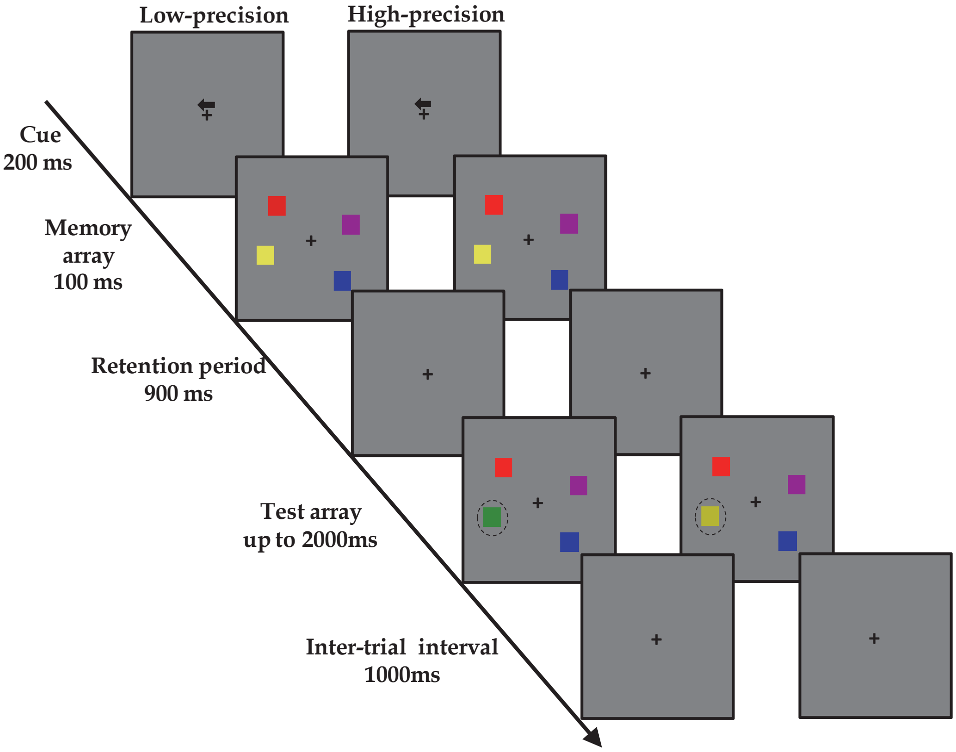

FIGURE 12 Trial schematic of the low- and high-precision conditions in Experiment 3. The dashed circle was not presented during the experiment but was used to mark the changed item for visualisation.

Three levels of set size (two, three and four) and two levels of precision conditions (high-precision and low-precision) were varied. The two precision conditions were blocked and counterbalanced across participants. There are a total of six conditions. Three set size conditions were intermixed within each block. Before the experiment started, participants practiced for at least 20 trials to ensure they understood the procedure. Each condition had 200 trials, resulting in a total of 1200 trials.

EEG recording and analyses

The procedures for ERP recording and analysis were similar to those used in Experiment 1 and 2, except the trials were segmented into 1200 ms epochs (from 100 ms to 1100 ms after the onset of the memory array).

CDA was measured at the posterior parietal (CP3/CP4, CP5/CP6, and P7/P8) as the difference in mean amplitude between ipsilateral and contralateral waveforms. A 300–900 ms measurement window was used to calculate the mean amplitude after the onset of memory array.

3.2.2 Results and discussion

Behavioural results

A two-way ANOVA with set size (two vs. three vs. four) and precision conditions (low-precision requirement vs. high-precision requirement) was conducted to determine VWM accuracy. Set size [$F(2,26) = 51.002$, $p < .001$] and precision condition [$F(1,13) = 94.037$,$p < .001$] had a significant main effect. The interaction between the set size and precision condition was also significant [$F(2,26) = 28.429$, $p < .001$]. Planned comparisons were conducted and showed that set size had a main effect only in the low-precision condition [$F(2,26) = 66.603$, $p < .001$], not in the high-precision condition [$F(2,26) = 2.135$, $p = .14$] (Figure 13a). These results suggest that participants performed better in the low-precision condition than in the high-precision condition.

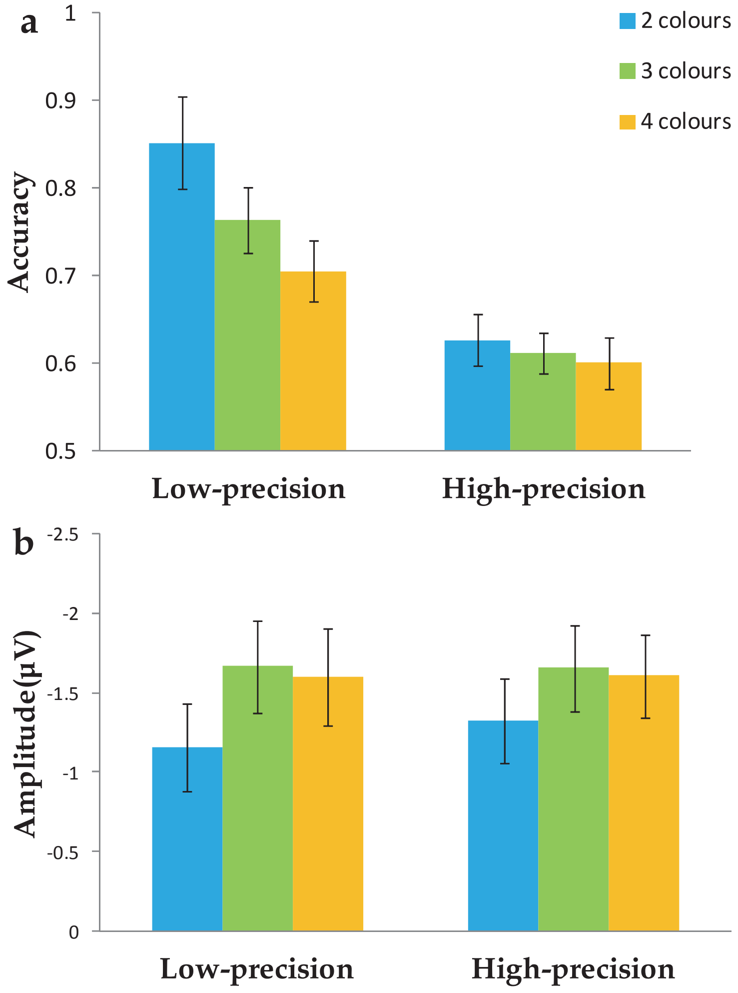

FIGURE 13 The (a) behavioural and (b) CDA amplitude results of Experiment 3. Error bars are standard error of the mean

ERP results

Figure 14 displays the CDA time-locked to the onset of the memory array for each set size in different precision conditions. A two-way ANOVA with set size (two vs. three vs. four) and precision conditions (low-precision requirement vs. high-precision requirement) was conducted to determine CDA amplitude. Set size [*F*(2,26) = 7.445, *p* < .01] had a significant main effect, but neither the main of precision condition [*F*(1,13) = 0.247, *p* = .63] nor the interaction between set size and precision condition was significant [*F*(2,26) = 0.510, *p* = .60].

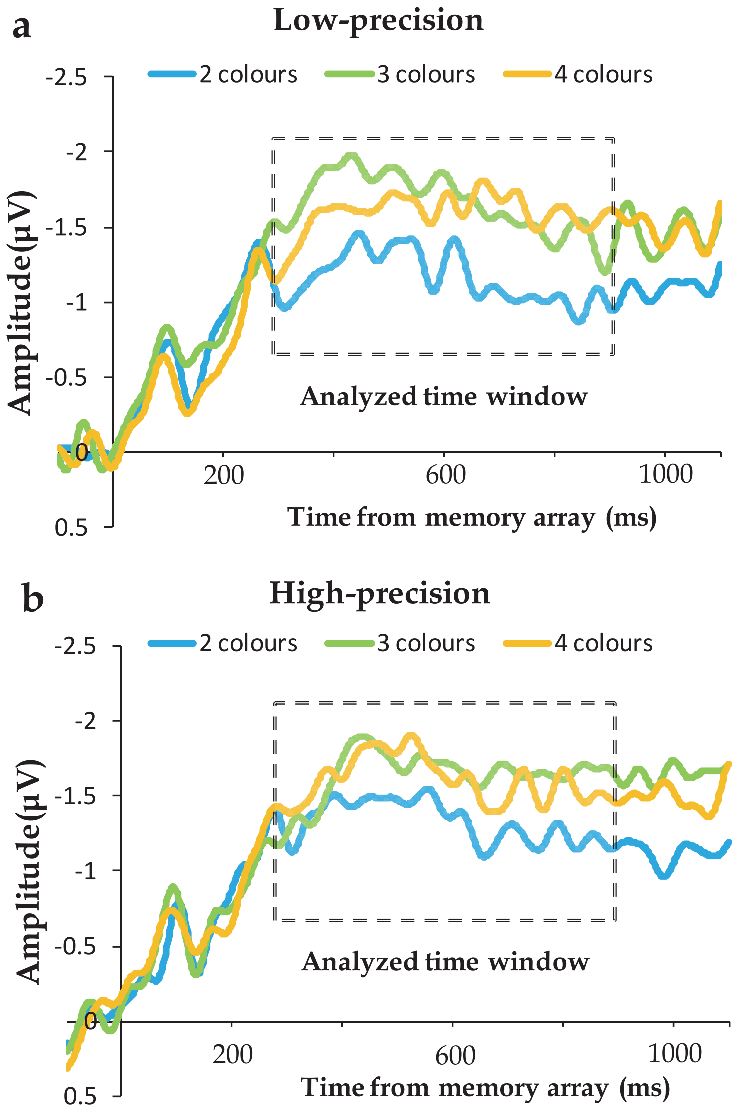

FIGURE 14 Grand-averaged CDA difference waves of the low- and high-precision conditions in Experiment 3. The waves were time-locked to the onset of the memory array.

Planned comparisons showed that, in the low-precision condition, the CDA amplitude of the two-colour condition was smaller than that of the three-colour condition [$t(13) = 2.756$, $p < .05$]. However, the CDA amplitude of the three-colour condition was not significantly different from that of the four-color condition [$t(13) = -0.394$, $p = .70$] (Figure 13b). A similar result pattern was also shown for the high-precision condition [$t(13) = 2.892$, $p < .05$ for two-colour condition vs. three-colour condition; $t(13) = -0.366$, $p = .72$ for three-colour condition vs. four-colour condition].

The goal of Experiment 3 is to examine the relationship between VWM quantity limitation and the required task precision for colour materials by using the CDA component to indicate the VWM quantity limitation. Although the behavioural results showed that tasks with different precision conditions vary in difficulty, equivalent CDA amplitudes were observed in low- and high-precision conditions, which suggested that in these conditions, the set size and number of colours stored in VWM were the same. More importantly, the CDA amplitudes in both precision conditions reached an asymptote for memorisation of three colours. This suggested that participants' VWM quantity limitation was maintained at three colours in both low- and high-precision conditions.

3.3 Discussion of Study II

There was a discrepancy between the behavioural and ERP results. This might be due to the fact that the ERP reflects mostly automatic processing, which could be more sensitive than behavioural measures to the information stored in VWM. However, behavioural performance showed a large difference in overall accuracy across the two precision conditions, demonstrating that manipulation of precision demand was effective. Moreover, equivalent CDA amplitude was observed in the low- and high-precision conditions, suggesting that CDA was not influenced by task difficulty in general.

The results of Study II showed that, when memorising colour materials, the VWM quantity limitation was not affected by the VWM precision required by a given task. The results are confirmed by a similar study (He, Zhang, Li, & Guo, 2015) but are different from the previous research on orientation materials. There are two possibilities to explain the difference in results.

One possibility is that, because of the differences in VWM encoding for colour and orientation materials, there are genuine differences in the manner of VWM resource allocation for colour features and other visual features. This possibility seems to be supported by the classic slot model, which suggests that there is no trade-off between VWM quantity limitation and precision and individuals cannot voluntarily allocate VWM resources based on task requirements. However, because the classical slot model does not explain the results of many VWM studies (Bays & Husain, 2008; Zhang & Luck, 2008), another explanation of the different results is proposed here: it is possible that no evidence of a trade-off between quantity and precision was found due to the relatively short exposure duration of the memory array in this experiment. In other words, it may take more time to implement such a trade-off. Because a previous study has found that the time needed for consolidating colour materials is shorter than that for orientation materials (Vogel et al., 2006), researchers often choose shorter exposure duration for colour stimuli than for orientation stimuli in VWM tasks. One study supported the hypothesis that individuals could voluntarily trade off between VWM quantity limitation and VWM precision for orientation stimuli and used an exposure duration of 500 ms (Gao et al., 2011). However, only an exposure duration of 100 ms was employed in Study II.

Therefore, Study II could only suggest that, for a short duration of exposure to a memory array, there is no evidence that individuals can voluntarily trade off between VWM quantity limitation and precision for colour materials. Although there are two possible explanations for the results, these possibilities cannot be confirmed by the results of Study II. It is necessary to test these possibilities by examining whether the manner of the trade-off (involuntary or voluntary) between VWM quantity and precision is influenced by other factors. In the follow-up studies, another experimental paradigm was used to further investigate this issue.

4 STUDY III: IMPACT OF SET SIZE AND EXPOSURE DURATION ON TRADE-OFF MANNER BETWEEN VWM NUMBER AND PRECISION

4.1 Introduction

As proposed in Study II, the exposure duration of the memory array may affect the voluntary trade-off between VWM number and precision. In fact, even for orientation stimuli, there is still debate about whether individuals can voluntarily trade off between VWM number and precision. Two different hypotheses have been proposed. The involuntary hypothesis suggests that the trade-off between VWM number and precision may be only based on the number of items needed to be memorised; that is, via stimulus-driven factors (Murray, Nobre, Astle, & Stokes, 2012). The voluntary hypothesis suggests that the trade-off between VWM number and precision could be based on the task requirement; that is, via voluntary control (Gao et al., 2011; Machizawa et al., 2012). However, it is possible that the involuntary and voluntary hypotheses are not mutually exclusive. It should be noted that studies supporting the involuntary hypothesis have used a very short exposure duration of the memory array, such as 50 ms/item (Murray et al., 2012). However, a longer exposure duration was used in studies supporting the voluntary hypothesis, such as 125 ms/item (Gao et al., 2011; Machizawa et al., 2012). It is noteworthy that the length of exposure duration of the memory array affects the VWM consolidation process (Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011). Therefore, it is necessary to explore how exposure duration and memory set size affect the manner of trade-off between VWM number and precision.

As shown in Study I and II, the use of CDA components can clearly indicate the number of items stored in VWM. However, one problem with CDA components is that they can only be used to indicate the VWM number or VWM quantity limitation – they cannot indicate VWM precision. That is, the ERP technique cannot simultaneously observe the VWM number index and the VWM precision index. For exploring the trade-off relationship between VWM number and precision, a paradigm for observing both indices at the same time was needed. Thus, the orientation recall task was chosen as the paradigm in Study III. By using different exposure durations and set sizes of the memory array, the manner of trade-off between VWM number and precision was investigated.

4.2 Experiment 4 - Trade-off between VWM precision and number in short exposure duration and high memory set size

The aim of Experiment 4 was to investigate whether participants can carry out the trade-off between VWM number and precision according to the task requirement under the short exposure duration and high memory set size conditions. By using different feedback rules to manipulate the precision requirement, participants were asked to memorise four orientations of 200 ms exposure duration in a high-precision requirement condition and a low-precision requirement condition. If the VWM number index and the VWM precision index were different under different precision conditions, then this meant that participants could voluntarily trade off between the VWM number and precision. On the contrary, if no difference between the VWM number index and the VWM precision index under different precision conditions was found, then this would indicate that participants could not trade off between the VWM number and precision under the short exposure duration and high memory set size conditions.

4.2.1 Methods

Participants

A total of 47 participants (42 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

Participants viewed the display at a distance of 60 cm, and the stimuli were presented on a 19-inch LCD monitor (1280×768 pixel) in a dark room. The memory stimuli were sinusoidal gratings ($0.90^{o}\times 0.90^{o}$), which may be presented in four possible locations.

Procedure

Participants completed an orientation recall task in a high-precision condition and a low-precision condition. Each trial began with a 200-ms fixation dot, followed by a-200 ms memory array of four orientations. After the memory array disappeared, a 1000-ms blank period followed, after which a location cue for the recall response was given. The location cue was presented at one of the memory stimuli's locations, along with an adjustable orientation. Participants were asked to adjust the orientation in the test array to match that of the cued orientation by using the mouse. Participants were told that they could keep adjusting until they felt satisfied. After they finalised the response, feedback about the response result was presented on the screen (Figure 15). Three different values were contained in the feedback: 'offset', 'score' and 'total score'. The 'offset' represented the degree difference between the actual orientation and the reported orientation. The 'score' represented the number of scores participants earned on this trial. The 'total score' represented the number of scores accumulated in this condition of the experiment. Two different precision conditions were manipulated by the earning points rule in the feedback. In the high-precision condition, participants earned six scores if their offset was less than 10° but earned nothing otherwise. In the low-precision condition, participants earned four scores if their offset was less than 30° and earned nothing for offsets between 30° and 50°. To encourage participants to store more items in the low-precision condition, they were penalized two scores for offsets greater than 50°. Each participant had a base of 100 points at the beginning. The reward rule was told to them before the experiments. Participants were encouraged to get more scores in the experiments.

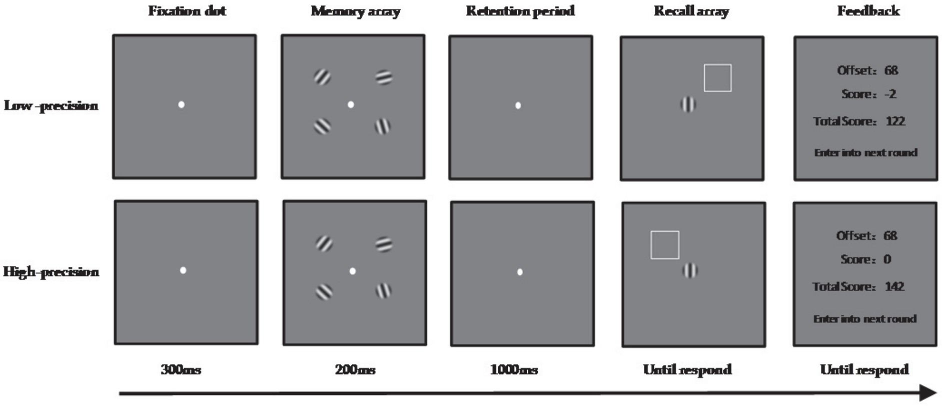

FIGURE 15. Trial schematic of the low- and high-precision conditions in Experiment 4.

The high- and low-precision conditions were blocked and counterbalanced across participants. Before the experiment started, participants practised for at least 20 trials to ensure they understood the procedures. Each precision condition had 280 trials, for a total of 560 trials.

Data analysis

Because the participants needed time to form appropriate strategies through feedback, the first 80 trials in each precision condition were not analysed; accordingly, the results were generated based on the remaining 200 trials.

The difference between the target orientation and participants' orientation setting was calculated as an offset value. By using the standard mixture model to fit the data (Zhang & Luck, 2008), two independent parameters were determined by maximum likelihood estimation: the guess rate (P_g), which represents the percentage of guess rate in each condition; and the precision index (SD), which is inversely related to VWM precision and was therefore considered the VWM precision index. The number of memory items (K) was calculated as set size×(1 -P_g) and considered the VWM number index.

In addition to the mixture model, I also tested other models (swap model and variable precision model) to fit the data from this study. I generally observed highly consistent results no matter which fitting model was used. For the sake of brevity, only the results of the mixture model are reported in the dissertation. More details about additional modelling results can be found in the supplemental materials of Article III.

4.2.2 Results and discussion

For a visualisation aid, the mixture model was fitted to the aggregate data (Figure 21 a-b), and averaged parameters of the mixture model for individual fits.

For the precision index (SD), there was no significant difference between the low-precision condition and the high-precision condition [*t*(46) = 0.442, *p* = .661]. A similar result pattern was found in the VWM number index (*K*) [*t*(46) = 0.200, *p* = .842] (Figure 16). These results showed that participants could not achieve higher memory precision in the high-precision condition than in the low-precision condition.

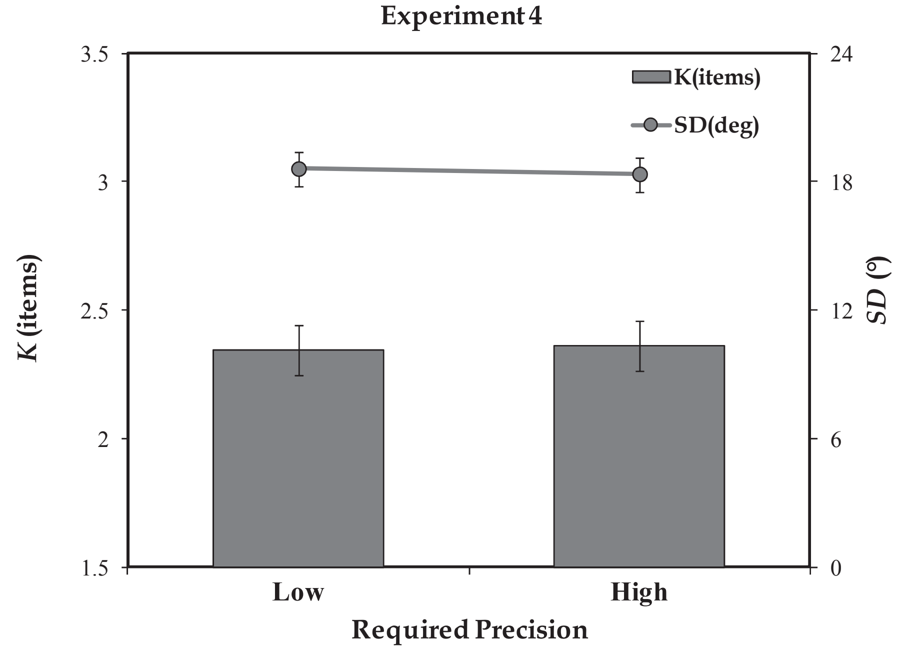

FIGURE 16. The results of the low- and high-precision conditions in Experiment 4. Error bars represent the standard error of the mean.

These results suggest that under the condition of high memory set size and short exposure duration, participants could not perform a trade-off between VWM precision and number according to the task requirements.

4.3 Experiment 5 - Trade-off between VWM precision and number in short exposure duration and low memory set size

The aim of Experiment 5 was to investigate whether participants could carry out the trade-off between VWM number and precision according to the task requirement under the short exposure duration and low memory set size conditions.

4.3.1 Methods

Participants

A total of 50 new participants (42 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

The stimuli used in Experiment 5 were identical to those used in Experiment 4.

Procedure

The procedures for Experiment 5 were identical to those for Experiment 4, except that the memory set size in the memory array was reduced from four to two (Figure 17). The memory array orientations were presented in two random locations among the four possible locations.

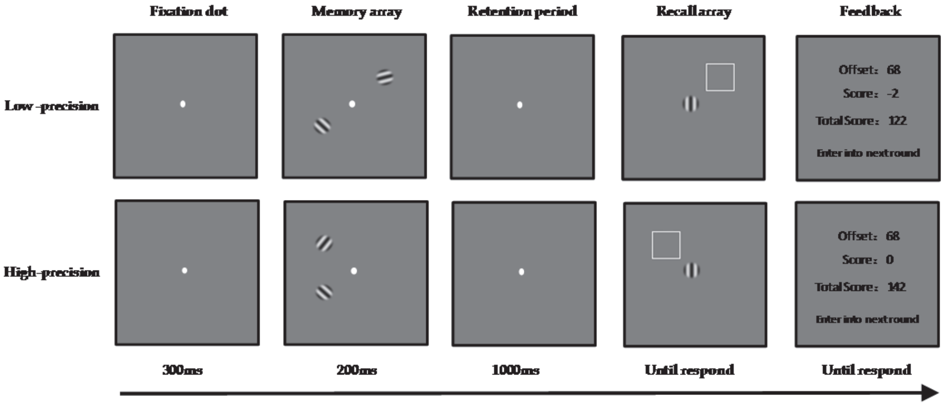

FIGURE 17. Trial schematic of the low- and high-precision conditions in Experiment 5.

Data analysis

The data analysis steps for Experiment 5 were identical to those for Experiment 4.

4.3.2 Results and discussion

For a visualisation aid, the mixture model was fitted to the aggregate data (Figure 21 c-d), and averaged parameters of the mixture model for individual fits.

The precision index (SD) in the low-precision condition was significantly higher than that in the high-precision condition [$t(49) = 7.355$, $p < .001$]. For the VWM number index (K), no significant difference was observed between the low-precision condition and the high-precision condition [$t(49) = 0.681$, $p = .499$] (Figure 18). The results suggest that although the same number of items were retained in high- and low-precision conditions, VWM precision was higher in the high-precision condition than in the low-precision condition.

In addition, two mixed-factor analyses of variance (ANOVA) taking precision condition (high- vs. low-precision) as a within-subject factor and experiment (Experiment 4 vs. 5) as a between-subjects factor on the SD and K parameters were respectively conducted. For SD, there was a significant main effect of precision [$F(1,95) = 18.933$, $p < .001$] and a significant interaction between precision and experiment [$F(1,95) = 12.916$, $p < .001$], yet the main effect of experiment was not significant [$F(1,95) = 1.418$, $p = .237$]. Furthermore, analyses of simple effects showed that in the high-precision condition, the main effect of experiment was significant [$F(1,95) = 6.20$, $p < .05$]; while in the low-precision condition, the main effect of experiment was not significant [$F(1,95) = 0.25$, $p = .619$] for SD. The mixed-factor ANOVA for the K parameter found only the main effect of experiment to be significant [$F(1,95) = 35.916$, $p < .001$], with neither the main effect of precision [$F(1,95) = 0.003$, $p = .954$] nor the interaction between precision and experiment [$F(1,95) = 0.194$, $p = .661$] reaching significance.

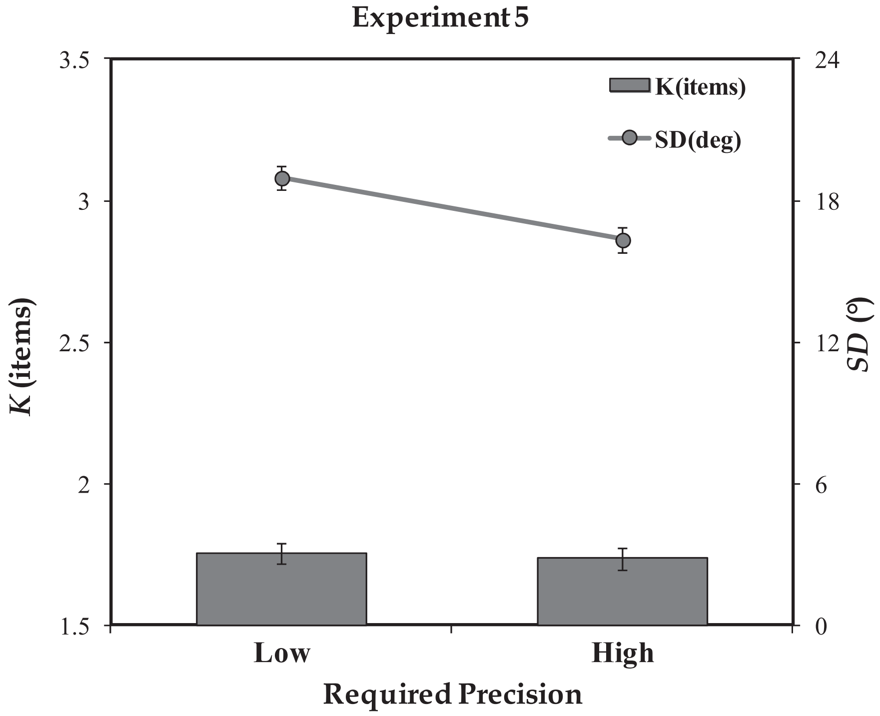

FIGURE 18. The results of the low- and high-precision conditions in Experiment 5. Error bars represent the standard error of the mean.

These results suggest that under the condition of low memory set size and short exposure duration, participants could improve VWM precision according to the task requirements while maintaining the same number of memory items in different precision conditions.

4.4 Experiment 6 - Trade-off between VWM precision and number in long exposure duration and high memory set size

The aim of Experiment 6 was to investigate whether participants could carry out the trade-off between VWM number and precision according to the task requirement under the long exposure duration and high memory set size conditions.

4.4.1 Methods

Participants

A total of 49 new participants (41 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

The stimuli used in Experiment 6 were identical to those used in Experiments 4 and 5.

Procedure

The procedure was identical to that used in Experiment 4, except that the exposure duration of the memory array was increased from 200 ms to 500 ms (Figure 19).

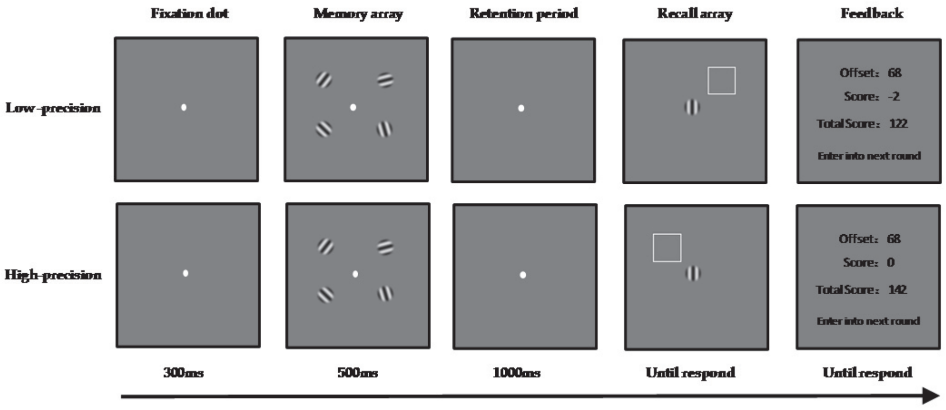

FIGURE 19. Trial schematic of the low- and high-precision conditions in Experiment 6.

Data analysis

The data analysis steps for Experiment 6 were identical to those for Experiment 5.

4.4.2 Results and discussion

For a visualisation aid, the mixture model was fitted to the aggregate data (Figure 21 e-f), and averaged parameters of the mixture model for individual fits.

The precision index (SD) in the low-precision condition was significantly higher than that in the high-precision condition [$t(48) = 6.177$, $p < .001$]. The VWM number index (K) in the low-precision condition was significantly larger than that in the high-precision condition [$t(48) = 5.478$, $p < .001$] (Figure 20). The results suggest that participants had a larger number but lower precision for VWM representations in the low-precision condition than in the high-precision condition.

In addition, two mixed-factor ANOVAs taking precision condition (high- vs. low-precision) as a within-subject factor and experiment (Experiment 4 vs. Experiment 6) as a between-subjects factor on the SD and K parameters were respectively conducted. For SD, there was a significant main effect of precision [*F*(1,94) = 24.014, *p* < .001] and a significant interaction between precision and experiment [*F*(1,94) = 18.625, *p* < .001], but the main effect of experiment was not significant [*F*(1,94) = 1.158, *p* = .285]. Furthermore, analyses of simple effects showed that the main effect of experiment was significant in the high-precision condition [*F*(1,94) = 8.18, *p* < .01] but was not significant in the low-precision condition [*F*(1,94) = 1.77, *p* = .187]. For K, the ANOVA showed that the main effect of precision was significant [*F*(1,94) = 16.006, *p* < .001]; the interaction between precision and experiment was also significant [*F*(1,94) = 18.159, *p* < .001], but the main effect of experiment was not significant [*F*(1,94) = 0.820, *p* = .367]. Furthermore, simple effects analyses showed that the main effect of experiment was not significant in the high-precision condition [*F*(1,94) = 0.70, *p* = .406], but it was significant in the low-precision condition [*F*(1,94) = 5.64, *p* < .05].

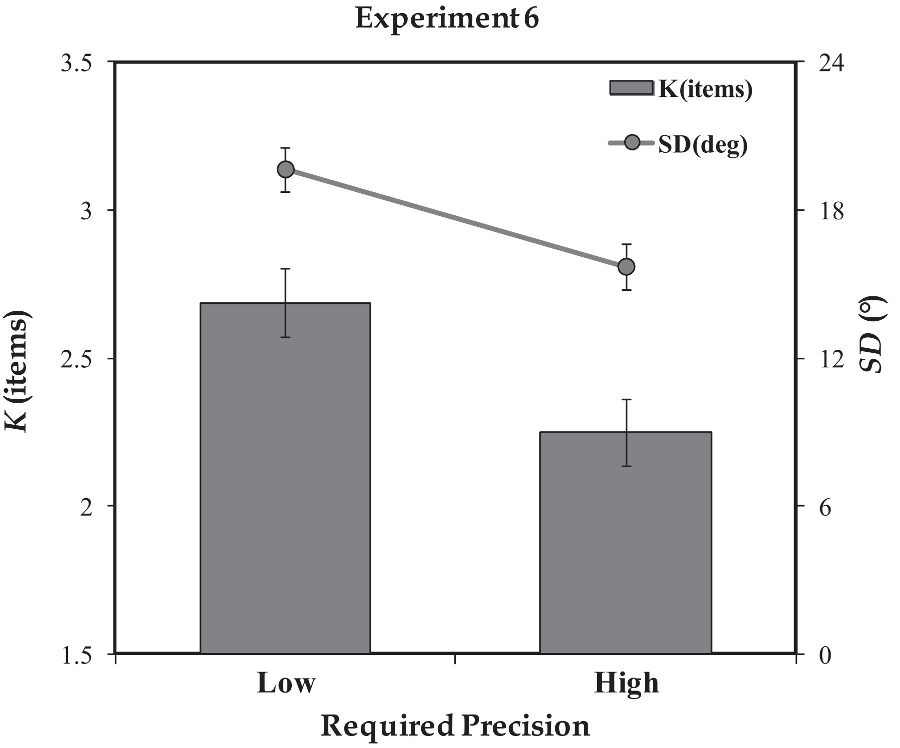

FIGURE 20. The results of the low- and high-precision conditions in Experiment 6. Error bars represent the standard error of the mean.

These results suggest that under the condition of high memory set size and long exposure duration, participants could trade off between the VWM number and precision according to the task requirements.

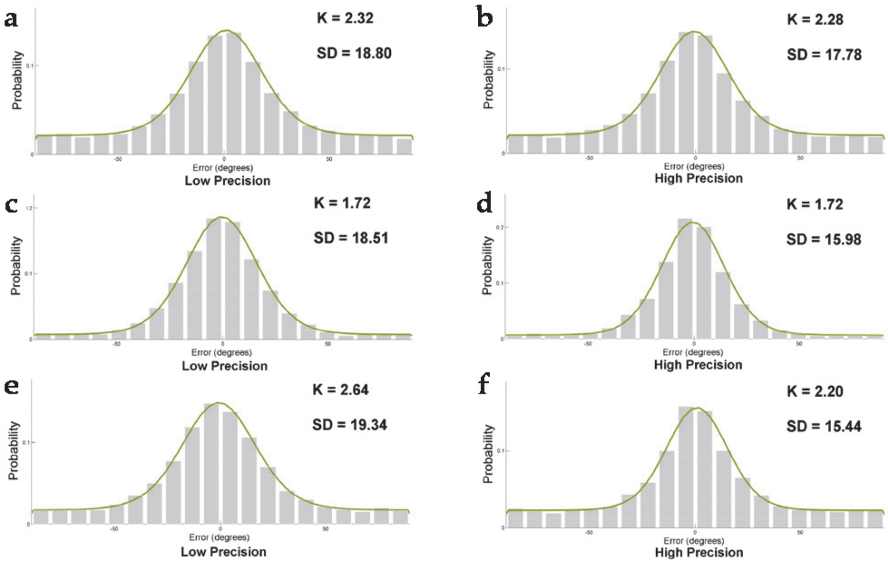

FIGURE 21. The model fitting results to aggregate data in (a)-(b) Experiment 4, (c)-(d) Experiment 5 and (e)-(f) Experiment 6. The probability density functions for the offset in the (left column) low-precision and (right column) high-precision conditions are shown.

4.5 Discussion of Study III

The results of Study III show that participants could only control the trade-off between VWM number and precision according to the task requirements under short exposure duration and high memory set size (Experiment 4). However, they could control VWM precision according to the task requirements when the memory set size was low (Experiment 5) or the exposure duration was long (Experiment 6). These findings show that other factors affected whether participants could voluntarily trade off between the VWM number and precision. A two-phase VWM resource allocation model can be proposed to explain these results. The two-phase VWM resource allocation model suggests that the VWM resource can only be allocated in a stimulus-driven way in the early phase of VWM consolidation. However, when VWM consolidation time is sufficient to enable participants to complete the early phase, the allocation can enter the second phase of consolidation. In the second phase, participants can allocate resources flexibly and voluntarily according to task demands. The higher the number of items that need to be remembered, the longer the VWM consolidation time that will be needed for participants to enter the second voluntary phase from the first involuntary phase. More details about the two-phase VWM resource allocation model can be found in 8.2.

However, in addition to the effects of external factors such as exposure duration and the number of items that need to be remembered, internal factors of participants may also affect the manner of trade-off between VWM number and precision. The impact of internal factors (e.g. VWM capacity) on the trade-off between VWM number and precision was further explored in the follow-up study.

5 STUDY IV: IMPACT OF VWM CAPACITY ON TRADE-OFF ABILITY

5.1 Introduction

In Study III, orientation stimuli were used, and the results showed that participants could voluntarily allocate VWM resources in the late VWM resource allocation phase of the two-phase model. However, previous research using colour stimuli have suggested that VWM resources cannot be voluntarily allocated (Zhang & Luck, 2011). There are two possible explanations for this discrepancy in results.

The first possibility is that, similar to Study I, there are different consolidation mechanisms at work for orientation and colour materials, and thus different allocation mechanisms for them are also at work. It is reasonable to argue that the main property of an orientation stimulus is its boundary feature, while the main property of a colour stimulus is its surface feature. For these two types of stimulus, there could be different coding mechanisms – perhaps the two-phase model is valid for processing orientation stimuli, but not colour stimuli. Thus, when individuals need to store colour stimuli, they may only consolidate VWM representations based on a stimulus-driven VWM resource allocation, not on a voluntary VWM resource allocation. That is, there is no voluntary trade-off between VWM number and precision for colour materials.

The second explanation is that the two-phase model is also applicable to the processing of colour stimuli, but only when the exposure duration of the colour stimuli is sufficiently long (unlike the 200 ms used in Zhang and Luck [2011], which might have been too short). According to the two-phase model, if the process in the first phase is not sufficiently completed, VWM resource allocation will be involuntary, thereby preventing allocation according to the task requirements of memory resources. That is, participants could voluntarily trade off between VWM number and precision for colour materials when the exposure duration is sufficiently long. Thus, in order to explore the resource allocation pattern in the colour VWM task, exposure duration had to be manipulated.

In addition, previous studies have suggested that the ability to filter distractors is different in the high VWM capacity group and low VWM capacity group (Fukuda & Vogel, 2009; Vogel et al., 2005). Individuals with higher VWM capacity could perfectly filter distractors during the consolidation process. However, individuals with lower VWM capacity would consolidate distractors into VWM. The ability to voluntarily allocate resources and filter distractors is related to the capacity for top-down attention control. Although Study III found that external factors, such as exposure duration and memory set size, affect the trade-off manner between VWM number and precision, the impact of individual internal factors, such as VWM capacity, on the trade-off manner is still unknown. Thus, there is a possibility that low VWM capacity individuals cannot voluntarily allocate VWM resources according to task demands but must do so in a stimulus-driven way. To test this possibility, it is necessary to explore whether the two-phase model is applicable to individuals with different memory capacities.

Therefore, the purpose of Study IV was to further expand the two-phase model in two respects: First, to test the trade-off manner for storing colour in short exposure duration (Experiment 7) and long exposure duration (Experiment 8), designs similar to those used in Experiments 4 and 6 were adopted in Experiments 7 and 8, except that colours were used as materials. Second, to test the impact of different VWM capacity individuals, the trade-off manner of different VWM capacity participants was investigated by dividing them into a high VWM capacity group and a low VWM capacity group.

5.2 Experiment 7 - Impact of VWM capacity on trade-off ability in short exposure duration

5.2.1 Methods

Participants

A total of 26 participants (21 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

Participants viewed the display at a distance of 60 cm, and the stimuli were presented on a 19-inch LCD monitor (1280×768 pixel) in a dark room. In the change detection task described below, the memory array of six distinct colour stimuli ($0.65^{o}\times0.65^{o}$) was randomly displayed within a $9.8^{o}\times7.3^{o}$ region around a central fixation point. In the colour recall task described below, the memory array used consisted of colour stimuli (0.9°×0.9°) randomly selected from the colour set described above, with a minimum distance of 30° in colour space between items in the array.

Procedure

There were two sessions in the experiment. The participants first completed a change detection task to measure their VWM capacities. In this session, each trial began with a central fixation cross that appeared on the screen for 200 ms. A memory array was then presented for 500 ms. After a subsequent 1000-ms retention period, a test array lasting for 2500 ms was presented. A test colour was presented at the location of one of the colour squares in the memory array. Participants were asked to indicate whether the colour of the test array was identical in colour to the corresponding item in the sample array. Accuracy, rather than response speed, was stressed in this experiment.

After the first session was completed, participants had at least a five-minute break before beginning the colour recall task. In this session, participants were asked to perform a colour recall task in two precision conditions. Each trial started with the presentation of a fixation cross in the centre of the screen. Four colour squares were then presented for 200 ms. The sample squares could be presented in four possible positions, located at the four fixed corners (left-up, left-down, right-up, right-down) of an imaginary square. After a 1000-ms retention period, a test array was presented. The test array consisted of an outlined square at the location of one of the sample squares in the sample array in addition to a colour wheel. Participants were asked to indicate which colour exactly matched the colour of the test sample square by clicking on the corresponding location on the colour wheel (Figure 22). Participants were told that they could keep adjusting it until they felt satisfied. After they finalised their responses, feedback about the response results was presented on the screen. Then, participants were provided with feedback containing three values: ‘offset’, ‘score’ and ‘total score’, as in Experiment 4–6. By using similar rules to those in Experiment 4–6, the high- and low-precision conditions were manipulated by varying the reward points rule.

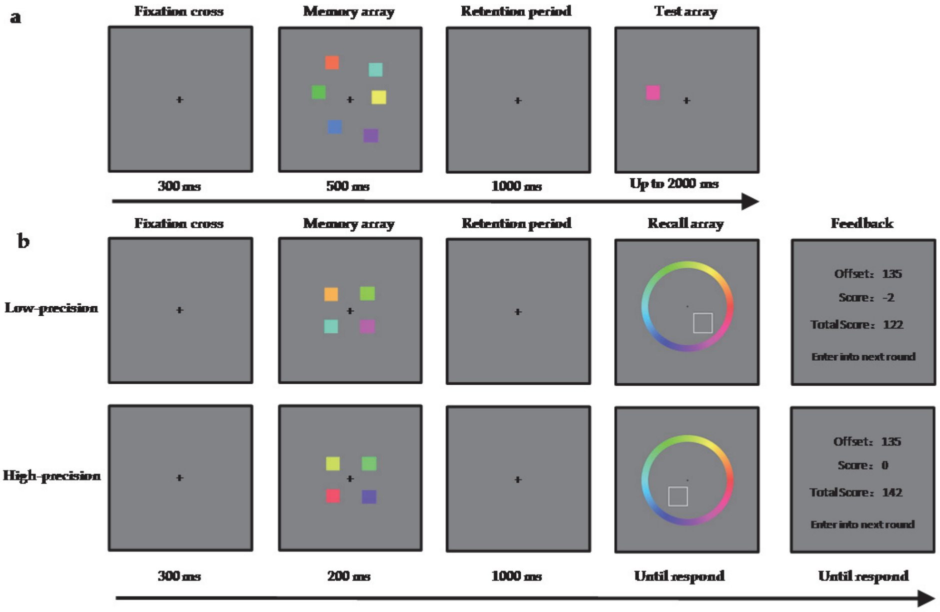

FIGURE 22. Trial schematic of the (a) change detection task and (b) colour recall task in Experiment 7.

Two levels of capacity groups (high VWM capacity and low VWM capacity) and two levels of precision (high-precision and low-precision) were varied. The two precision conditions were blocked and counterbalanced across participants. Before the experiment started, participants practised for at least 20 trials to ensure they understood the procedures. Each precision condition had 280 trials, for a total of 560 trials.

Data analysis

The VWM capacity (K_c) for each participant was measured in the change detection task by using Cowan's K formula (Cowan, 2001). Participants were divided into a high VWM capacity group and a low VWM capacity group by using a median split method.

In the colour recall task, similar to Experiment 4-5, the results were generated based on the last 200 trials. The offset value was calculated. By using the standard mixture model to fit the data (Zhang & Luck, 2008), the guess rate parameter (P_g) and precision parameter (SD) were observed by maximum likelihood estimation. To avoid confusing the K value (as in Experiments 4–6) and K_c value, the correct reporting rate (P_m) was calculated as 1 -P_g, which was considered as the VWM number index in the follow-up experiments.

In addition to the mixture model, I also tried using a swap model to fit the data from this study. I generally observed highly consistent results no matter which fitting model was used. For the sake of brevity, only the results of the mixture model are reported in the dissertation. More details about these additional modelling results can be found in the supplemental materials of Article IV.

5.2.2 Results and discussion

VWM capacity

By using the median split of their VWM capacity estimates, participants were divided into a high-capacity group (K_c = 3.24 ± 0.59) and a low-capacity group (K_c = 1.81 ± 0.48), resulting in 13 participants in each group.

Colour recall task

For a visualisation aid, the mixture model was fitted to the aggregate data (Figure 23), and averaged parameters of the mixture model for individual fits.

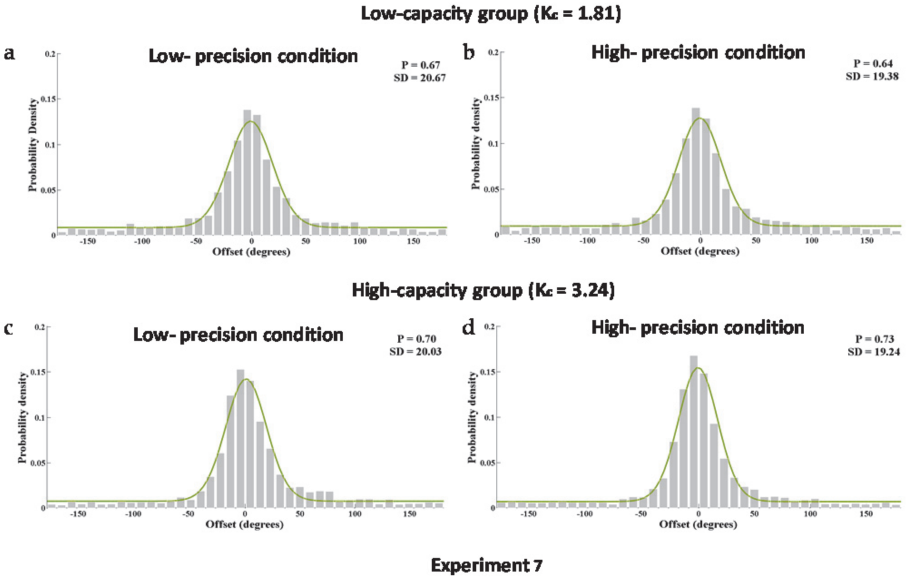

FIGURE 23.The model fitting results to aggregate data of the (a) low-capacity group and (b) high-capacity group in Experiment 7. The probability density functions for the offset in the (left column) low-precision and (right column) high-precision conditions are shown.

For the precision index (SD), a two-way ANOVA with precision conditions (low precision vs. high precision) and VWM capacity (low VWM capacity vs. high VWM capacity) as factors yielded no significant main effect of precision condition [$F(1,24) = 0.883$, $p = .357$] and VWM capacity [$F(1,24) = 0.129$, $p = .722$]. The interaction between precision condition and VWM capacity was also not significant [$F(1,24) = 0.053$, $p = .820$].

For the memory number index (P), a two-way ANOVA with precision conditions (low precision vs. high precision) and VWM capacity (low VWM capacity vs. high VWM capacity) as factors yielded no significant main effect of precision condition [$F(1,24) = 0.002$, $p = .967$] and VWM capacity [$F(1,24) = 1.604$,

p = .218,]. The interaction between precision condition and VWM capacity was also not significant [$F(1,24) = 1.827$, p = .189] (Figure 24).

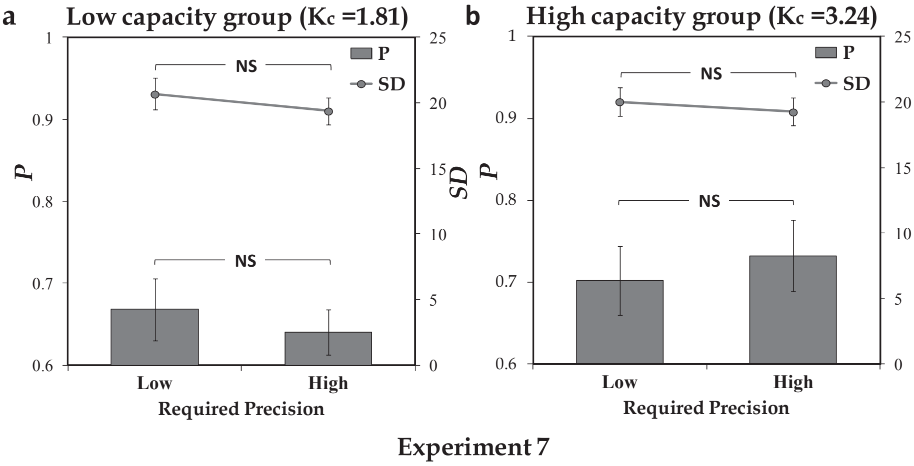

FIGURE 24. The results of the (a) low-capacity group and (b) high-capacity group in Experiment 7. Error bars represent the standard error of the mean.

The results suggest that participants of both high- and low-capacity groups were unable to trade off between number and precision in VWM when exposure duration was short. That is, the trade-offs appeared to be based on stimulus-driven factors, regardless of the task demands. This suggests that there was an involuntary VWM resource allocation at this exposure duration.

5.3 Experiment 8 - Impact of VWM capacity on trade-off ability in long exposure duration

As explained in Study III, the two-phase model suggests that when the exposure duration is sufficiently long, trade-offs will be emerge in the voluntary allocation phase. In this experiment, the same procedure was used as in Experiment 7, but the exposure duration of the memory items was extended from 200 ms to 500 ms, and a test was performed to determine whether the VWM number and precision could be traded off in VWM.

5.3.1 Methods

Participants

A total of 26 new participants (23 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

The stimuli used in Experiment 8 were identical to those used in Experiment 7.

Procedure

The procedure used in Experiment 8 was identical to the one used in Experiment 7, except that the exposure duration of the memory array was increased from 200 ms to 500 ms (Figure 25).

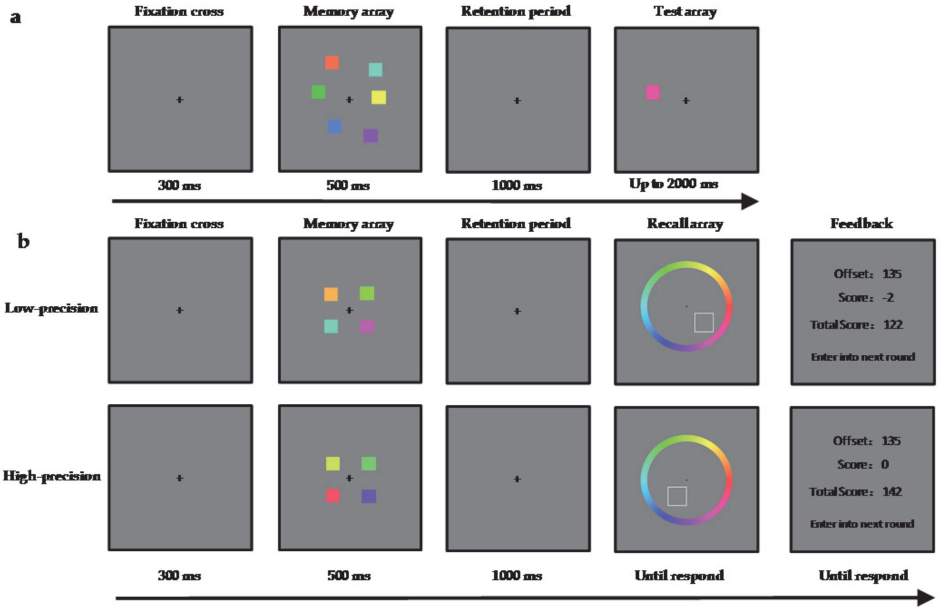

FIGURE 25. Trial schematic of the (a) change detection task and (b) colour recall task in Experiment 8.

Data analysis

The data analysis steps in Experiment 8 were identical to those used in Experiment 7.

5.3.2 Results and discussion

VWM capacity

By using the median split of their VWM capacity estimates, participants were divided into a high-capacity group ($K_c = 3.41 \pm 0.56$) and a low-capacity group ($K_c = 1.89 \pm 0.58$), resulting in 13 participants in each group.

Colour recall task

For a visualisation aid, the mixture model was fitted to the aggregate data (Figure 26), and averaged parameters of the mixture model for individual fits.

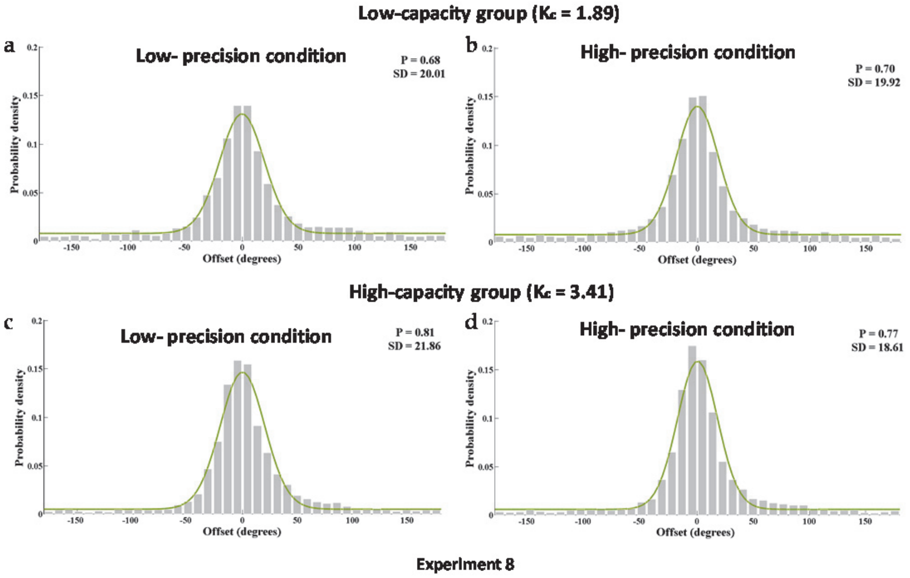

FIGURE 26.The model fitting results to aggregate data of the (a) low-capacity group and (b) high-capacity group in Experiment 8. The probability density functions for the offset in the (left column) low-precision and (right column) high-precision conditions are shown.

For the precision index (SD), a two-way ANOVA with precision conditions (low precision vs. high precision) and VWM capacity (low VWM capacity vs. high VWM capacity) as factors yielded a significant main effect of precision condition [$F(1,24) = 13.015$, $p < .01$] but no significant main effect of VWM capacity [$F(1,24) = 0.062$, $p = .805$]. However, the interaction between precision condition and VWM capacity was significant [$F(1,24) = 7.097$, $p < .05$].

For the memory number index (P), a two-way ANOVA with precision conditions (low precision vs. high precision) and VWM capacity (low VWM capacity vs. high VWM capacity) as factors yielded a significant main effect of VWM capacity [$F(1,24) = 4.959$, $p < .05$] but no significant main effect of precision condition [$F(1,24) = 0.812$, $p = .377$]. However, the interaction between precision condition and VWM capacity was significant [$F(1,24) = 6.625$, $p < .05$].

Planned comparisons showed that in the high-capacity group, the memory precision of the high-precision condition was higher than that observed for the low-precision condition [$t(12) = 4.102$, $p < .001$ for SD], while the memory number of the high-precision condition was less than that observed for the low-precision condition [$t(12) = 2.621$, $p < .05$ for P]. In contrast, in the low-capacity group, there was no memory precision difference or memory number difference between the high-precision and low-precision conditions [*t*(12) = 0.732, *p* = .478 for SD; *t*(12) = 1.117, *p* = .286 for P] (Figure 27).

In addition, two mixed-factor ANOVAs taking precision condition (high- vs. low-precision) as a within-subject factor and VWM capacity (low VWM capacity vs. high VWM capacity) and experiment (Experiment 7 vs. Experiment 8) as a between-subjects factor on the P and SD parameters were conducted, respectively. For P, there was a significant main effect of VWM capacity [*F*(1,48) = 6.025, *p* < .05] and a significant interaction across precision condition, VWM capacity and experiment [*F*(1,48) = 5.909, *p* < .05], but no other significant main effect or interaction was found (all *p* >.112). For SD, there was a significant main effect of precision condition [*F*(1,48) = 4.135, *p* < .05], but no other significant main effect or interaction was found (all *p* > .294).

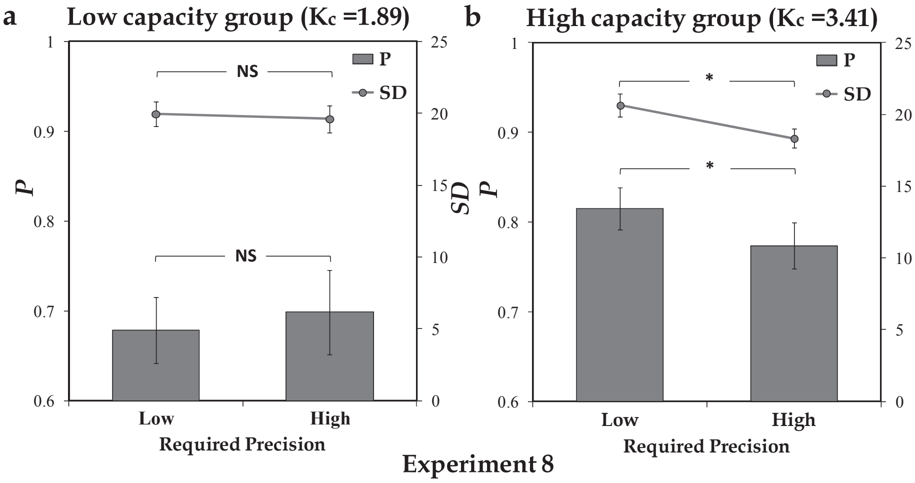

FIGURE 27. The results of the (a) low-capacity group and (b) high-capacity group in Experiment 8. Error bars represent the standard error of the mean.

These results, which were different from those found in Experiment 7, show that when the exposure duration of the sample array was increased from 200 ms to 500 ms for the high-capacity group, the precision in VWM was higher in the high-precision condition than in the low-precision condition, and the number of representations remaining in VWM was fewer in the high-precision than in the low-precision condition; whereas for the low-capacity group, there was no significant difference between the low-precision condition and the high-precision condition in terms of the precision or number of representations in VWM.

5.4 Discussion of Study IV

These results suggest that for colour stimuli, both high and low VWM capacity participants could not allocate VWM resources voluntarily according to task demands at a short exposure duration. When the exposure duration was longer, VWM resources could be allocated voluntarily in the high VWM capacity group, but not in the low VWM capacity group.

The results suggest that at least for high VWM capacity individuals, the two-phase model is still applicable to processing colour stimuli. For low VWM capacity individuals, there may be some constraints on the mechanism of VWM resource allocation, leading to a stimulus-driven involuntary allocation. Vogel et al.'s (2005) study suggested that low VWM capacity individuals fail to filter out irrelevant items. This may be in line with the idea that it might take extra effort to consolidate the memory selectively. Low VWM capacity individuals might forgo the extra selective processing because it is self-defeating or uncomfortably strenuous for them (Cowan & Morey, 2006). This may also encourage low VWM capacity participants to skip the voluntary resource allocation phase during consolidation for colour stimuli.

The results of Study IV suggest that exposure duration impacts the trade-off between VWM number and precision for colour stimuli. More importantly, the results suggest that VWM capacity also has an impact on the trade-off between VWM number and precision. Previous studies have suggested that individuals with low VWM capacity fail to filter out irrelevant items (Owens, Koster, & Derakshan, 2012; Vogel et al., 2005). Both these results and the present results may be explained by the same mechanism: For low VWM capacity individuals, the resources allocated to memory consolidation are very limited; filtering distractors and voluntary resource allocation require extra effort, which might drain too many resources from the consolidation process. Thus, low VWM capacity individuals experience an inability to filter distractors and voluntarily allocate VWM resources.

6 STUDY V: IMPACT OF BFA ON VWM RESOURCE ALLOCATION

6.1 Introduction

In Study V, the impact of external factors that display the location of the memory array on VWM resource allocation was investigated. More specifically, Study V explored the effect of BFA on the results of VWM resource allocation. Previous studies have suggested that BFA might arise from the VWM maintenance phase, when the memory items have disappeared (Umemoto, Drew, Ester, & Awh, 2010; Woodman & Vogel, 2008). For example, Umemoto et al. (2010) used an orientation recall task to test whether BFA occurs in the VWM maintenance phase. They found that even when memory items are presented sequentially, there was still a BFA in terms of VWM performance. These findings suggest that BFA is not caused by the structure of multiple stimuli presented at the same time, so BFA must occur in the VWM maintenance phase. In addition, they found that BFA increased the number of items stored in VWM, but not the precision of each representation.

However, according to Study III and IV, there should be a trade-off relationship between VWM number and precision – if BFA affects the number of items stored in VWM, it should also affect VWM precision when the memory set size is low. Umemoto et al. (2010) could not determine whether advantages for VWM precision were promoted because participants were asked to memorise too many items in their study. Limited VWM resources only allow stored items to obtain the lowest observable memory VWM, which might lead to no statistically significant difference between the bilateral and unilateral conditions.

Thus, to explore the effect of BFA on the VWM resource allocation results, it is necessary to explore whether BFA affects only the VWM number index, not the VWM precision index, under a low memory set size situation.

6.2 Experiment 9 - BFA in low memory set size

Experiment 9 used a recall procedure similar to the one used by Umemoto et al. (2010), except that a moderate number of memory items and a sufficient exposure duration were used in the present study. Participants needed to remember only two target items of four orientations in each trial to ensure that the set size was lower than the point at which VWM precision reaches asymptote (Zhang & Luck, 2008). Thus, participants had sufficient time to consolidate each target item into VWM. This avoided contamination caused by a lack of VWM consolidation time. In addition, a base line condition (single condition) was used for comparison with the unilateral and bilateral conditions.

6.2.1 Methods

Participants

A total of 19 participants (13 females) were recruited from the participant pool at Liaoning Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Liaoning Normal University.

Stimuli

Participants viewed the display at a distance of 60 cm, and the stimuli were presented on a 19-inch CRT monitor (800×600 pixel) in a dark room. The memory stimuli were sinusoidal gratings ($0.90^o \times 0.90^o$), which may be presented in four possible locations.

Procedure

Participants completed an orientation recall task. Each trial began with 200-ms arrow-cues above and below the fixation dot, followed by a 100-ms blank period; thereafter, a memory array of four orientations was presented. The arrow-cues were pointed in eight possible directions (‘left’, ‘right’, ’up’, ‘down’, ‘upper-left’, ‘lower-left’, ‘lower-right’, ‘upper-right’). After the memory array disappeared, a 1000-ms blank period followed, after which a location cue for the recall response was provided. The location cue was presented at one stimuli location, along with an adjustable orientation. Participants were asked to adjust the orientation in the test array to match that of the cued orientation by using the mouse. Participants were informed that they could continue to make adjustments until they were satisfied. After they had pressed the space bar to finalise their responses, feedback on their performance was presented for 1500 ms on the screen (Figure 28).

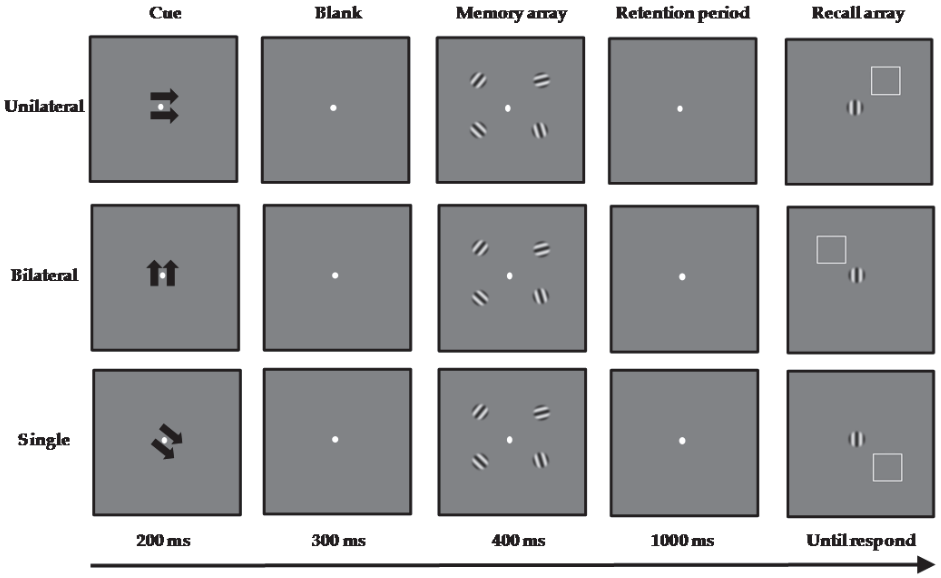

FIGURE 28. Trial schematic of the unilateral, bilateral and single conditions in Experiment 9.

The orientation directions were chosen randomly. Three different display conditions (unilateral, bilateral and single) were manipulated by varying the pointed directions of the arrow-cues. All conditions were intermixed within blocks. Before the experiment started, participants practised for at least 20 trials to ensure they understood the procedures. Each condition involved 120 trials, for a total of 360 trials.

Data analysis

The data analysis steps for Experiment 9 were identical to those for the recall task in Experiment 7-8. The offset value was calculated. By using the standard mixture model to fit the data (Zhang & Luck, 2008), the guess rate parameter (P_g) and precision parameter (SD) were observed by maximum likelihood estimation.

In addition to the mixture model, I tried using a swap model to fit the data from this study. I generally observed highly consistent results no matter which fitting model was used. For conciseness, only the results of the mixture model were reported in the dissertation. More details about these additional modelling results can be found in Article V.

6.2.2 Results and discussion

For a visualisation aid, the mixture model was fitted to the aggregate data for different display conditions (bilateral, unilateral, single; Figure 29 a-c), and averaged parameters of the mixture model for individual fits.

One-way ANOVAs with display conditions (bilateral vs. unilateral vs. single) for the precision index (SD) and guess rate (P_g) were conducted, respectively. For the SD, there was a significant main effect of display conditions [$F(2,36) = 34.03$, $p < .001$]. There was also a significant main effect of display conditions [$F(2,36) = 9.86$, $p < .01$] for the P_g.

Planned comparisons showed that the SD in the unilateral condition was significantly higher than that in the bilateral condition [$t(18) = 2.64$, $p < .05$]. The SD in the bilateral condition was significantly higher than that in the single condition [$t(18) = 5.30$, $p < .001$]. The P_g in the single condition was significantly lower than that in the bilateral condition [$t(18) = 3.34$, $p < .01$]. The P_g in the bilateral condition was not significantly different from that in the unilateral condition [$t(18) = 1.22$, $p = 0.239$] (Figure 29 d-e).

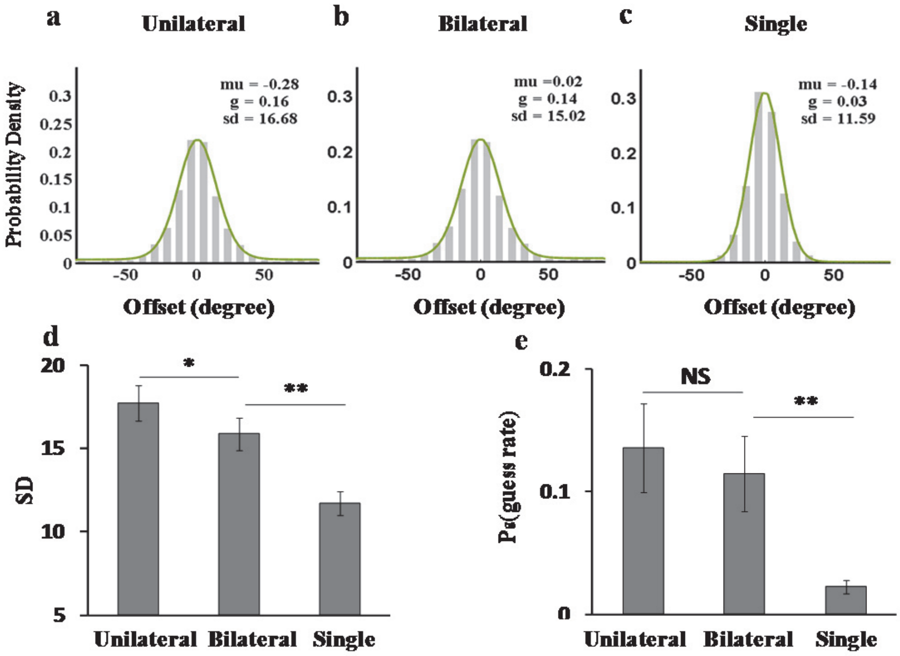

FIGURE 29. The model fitting results to aggregate data of the (a) unilateral, (b) bilateral and (c) single conditions. The (d) SD and (e) P_g results of the unilateral, bilateral and single conditions in Experiment 9. Error bars represent the standard error of the mean.

The results of Experiment 9 show that the SD for the unilateral condition was higher than that for the bilateral condition; in contrast, different results were not found between the unilateral and bilateral conditions regarding P_g. These results suggest that when the number of the memory set size is low, BFA increases VWM precision but does not affect the number of items stored in VWM. Because fewer items need to be stored in the single condition, the performance of the VWM number index and the precision index in the single condition was better than that in the unilateral condition and the bilateral condition.

It should be noted that Umemoto et al.'s (2010) study used shorter exposure durations (125–300 ms) than those in the present experiment. However, according to Study III and IV, different exposure durations of the memory array can lead individuals to different phases of resource allocation. In Experiment 9, participants had enough time to consolidate items. The effect of BFA on VWM resources was still unknown when participants' exposure durations were short.

6.3 Experiment 10 - BFA in different exposure durations

Experiment 10 manipulated the exposure duration (200 ms vs. 400 ms) to verify whether BFA in VWM could be affected by exposure duration.

6.3.1 Methods

Participants

A total of 16 participants (11 females) were recruited from the participant pool at Liaoning Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Liaoning Normal University.

Stimuli

The stimuli used in Experiment 10 were identical to those used in Experiment 9.

Procedure

The same procedures used in Experiment 9 were used in Experiment 10, except that the single condition was removed and a within-subjects manipulation of the presentation time was added (Figure 30). Two levels of exposure duration (200 ms and 400 ms) and two levels of the distribution condition (bilateral and unilateral) were varied. There were a total of four conditions, and the conditions were intermixed within the experiment. Before the experiment started, participants practised for at least 20 trials to ensure they understood the procedures. Each condition involved 80 trials, for a total of 320 trials.

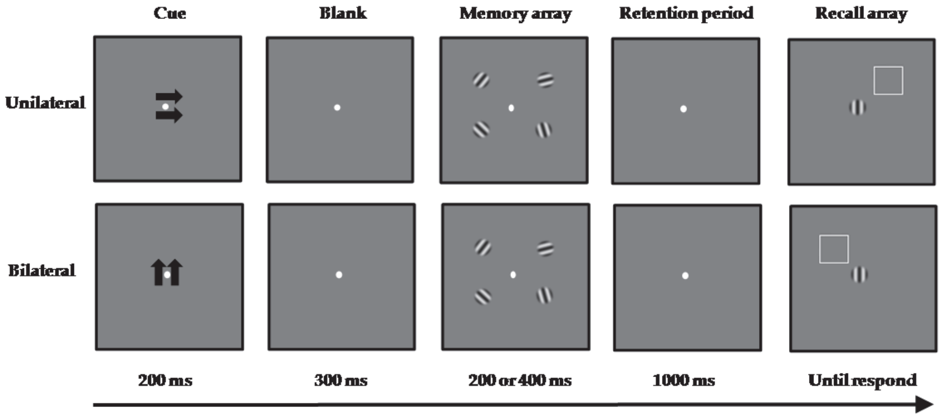

FIGURE 30. Trial schematic of the unilateral and bilateral conditions in Experiment 10.

Data analysis

The data analysis steps used in Experiment 10 were identical to those used in Experiment 9.

6.3.2 Results and discussion

For the precision index (SD), a two-way ANOVA with display (bilateral vs. unilateral) and exposure duration (200 ms vs. 400 ms) as factors yielded a significant main effect of display [$F(1,15) = 12.69$, $p < .05$] but no significant main effect of exposure duration [$F(1,15) = 1.55$, $p = .231$]. However, the interaction between the display and exposure duration was significant [$F(1,15) = 4.726$, $p < .05$]. For the guess rate (P_g), a two-way ANOVA with display (bilateral vs. unilateral) and exposure duration (200 ms vs. 400 ms) as factors yielded no main effect of display [$F(1,15) = 0.012$, $p = .915$], no main effect of exposure duration [$F(1,15) = 1.781$, $p = .202$], and no interaction between display and exposure duration [$F(1,15) = 1.578$, $p = .228$].

Planned comparisons showed that in the 200-ms condition, the SD of the bilateral condition was not significantly different from that of the unilateral condition [$t(15) = 0.387$, $p = .704$]. In the 400-ms condition, the SD of the bilateral condition was significantly lower than that of the unilateral condition [$t(15) = 2.998$, $p < .01$]. For the guess rate (P_g), planned comparisons showed that a significant difference between the bilateral and unilateral conditions was found only in the 200-ms condition [$t(15) = 2.202$, $p < .05$] (Figure 31). The results of Experiment 10 were in line with those of Experiment 9.

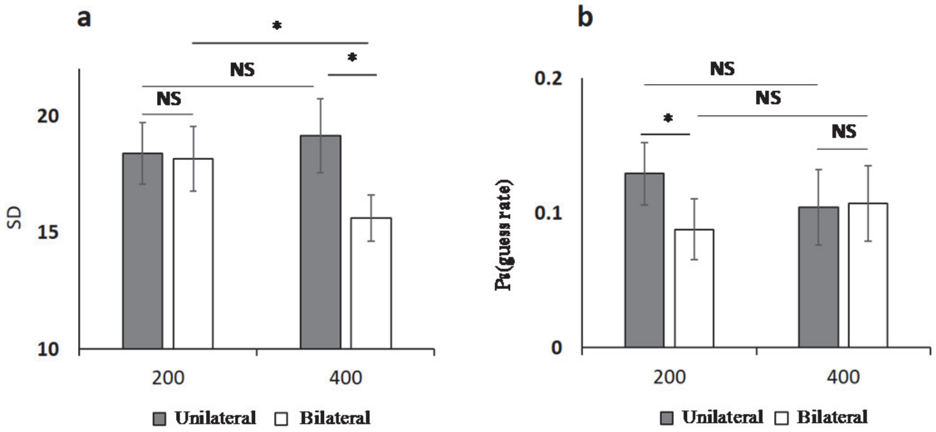

FIGURE 31. The (a) SD and (b) P_g results of the unilateral and bilateral conditions in Experiment 10. Error bars represent the standard error of the mean.

The results of 400-ms exposure duration were consistent with the results of Experiment 9. There was no VWM number difference between the unilateral and bilateral conditions, but VWM precision in the bilateral condition was higher than that in the unilateral condition. More importantly, a different result pattern was observed in the conditions under 200-ms exposure duration. The results in these conditions were similar to those in Umemoto et al.'s (2010) study. The guess rate in the unilateral condition was higher than that in the bilateral condition. This suggests that when VWM consolidation is insufficient, BFA could increase the number of items consolidated into VWM.

6.4 Experiment 11 - Influence of vertical and horizontal distribution of memory array on VWM

In Experiments 9 and 10, the memory targets tended to be presented horizontally in the bilateral condition and vertically in the unilateral condition. In order to ensure the validity of interpretation for BFA in Experiments 9 and 10, it was necessary to explore whether the bilateral advantages in these experiments were caused by the bilateral distribution or were simply caused by the horizontal distribution.

To test this issue, Experiment 11 required participants to only memorise the targets from the unilateral visual hemifield and manipulated the distribution of target items in a horizontal manner or in a vertical manner.

6.4.1 Methods

Participants

A total of 20 new participants (6 females) were recruited from the participant pool at Liaoning Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Liaoning Normal University.

Stimuli

The stimuli used in Experiment 11 were identical to those used in Experiments 9 and 10.

Procedure

The same procedures used in Experiment 10 for 400-ms conditions were used in Experiment 11, except that the presented area was moved 4.24^{o} to the left and right of centre so that the orientations were presented within a single hemifield. There were two conditions: vertical and horizontal. Two orientations were vertically presented at the near-left, far-left, near-right or far-right side of the centre in the vertical condition. Similarly, two orientations were horizontally presented at the top-left, bottom-left, top-right or bottom-right of the centre. To ensure the orientations were in the same hemifield in both vertical and horizontal conditions, the arrow-cues only pointed to the left or right directions. Participants were asked to only memorise the orientations of the pointed hemifield (Figure 32). The vertical and horizontal conditions were intermixed within the experiment. Before the experiment started, participants practised for at least 30 trials to ensure they understood the procedures. Each condition involved 120 trials per condition, for a total of 240 trials.

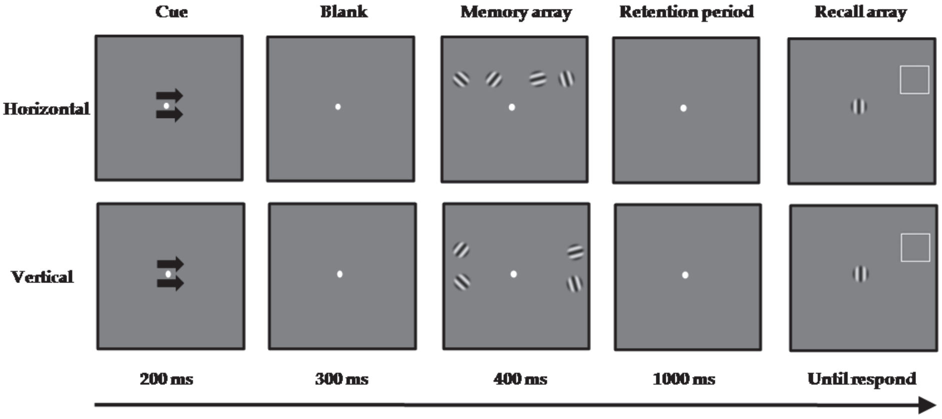

FIGURE 32. Trial schematic of the horizontal and vertical conditions in Experiment 11.

Data analysis

The data analysis steps in Experiment 11 were identical to those in Experiments 9 and 10.

6.4.2 Results and discussion

For the precision index (SD), there was no significant difference between the horizontal condition and vertical condition [$t(11) = -0.019$, $p = .985$]. A similar result pattern was found for the guess rate (P_g) [$t(11) = 0.716$, $p = .489$] (Figure 33).

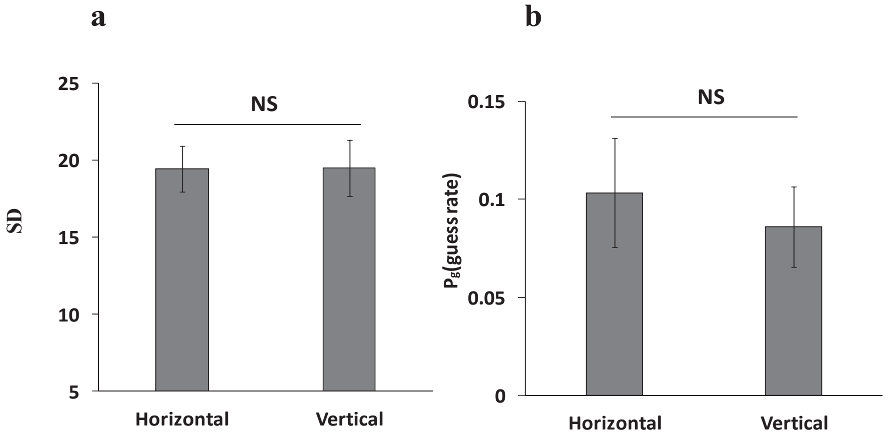

FIGURE 33. The (a) SD and (b) P_g results of the horizontal and vertical conditions in Experiment 11. Error bars represent the standard error of the mean.

The results of Experiment 11 show that there were neither VWM precision nor VWM number differences between the horizontal and vertical conditions. Therefore, the advantages found in Experiment 9 were caused by the memory target being presented in bilateral visual hemifields.

6.5 Discussion of Study V

The main purpose of Study V was to explore whether the precision of a bilateral memory array could be improved by reducing the number of the memory set size. In Experiment 9, the results provided evidence that BFA could arise in VWM precision when there is sufficient time, and that the memory set size was limited to two. The results of Experiment 10 replicated and extended Experiment 9. There was still a precision BFA at 400 ms; however, with a 200-ms presentation time, BFA disappeared in memory precision but reappeared in the guess rate. Previous studies have found that the advantage of bilateral distribution in VWM only improves memory probability in VWM; it does not affect memory precision (Umemoto et al., 2010). However, for the first time, Study V provided evidence that BFA could also increase VWM precision when the memory load was low and the exposure duration was long. In addition, these advantages are derived from the presentation of memory targets in bilateral visual hemifields rather than other distribution factors (Experiment 11). The reason for the differences between the previous study and Study V may be that participants were at different VWM resource allocation phases in these studies. The results of Experiment 11 suggest that the effect of BFA on VWM depends on the consolidation process. Thus, BFA affects both the VWM consolidation process and the VWM maintenance process. Further discussion can be found in 8.3.

7 STUDY VI: DIMENSION-BASED RETRO-CUE BENEFIT IN VWM RESOURCE ALLOCATION

7.1 Introduction

In Study I–V, the VWM resource allocation mechanism in the consolidation phase was investigated in different respects. Unlike the VWM consolidation process, which usually overlaps with the visual encoding process, resource allocation in the VWM maintenance phase is independent of the visual encoding process, which is only influenced by internal attention. Study VI further explored the effect of internal attention on resource allocation in the VWM maintenance phase.

As mentioned in the summary of the present research, the classic retro-cue task was modified based on the changed detection task by adding a retro-cue during the VWM maintenance phase. Recently, researchers have begun to explore the impact of internal attention on memory probability and VWM precision by combining the retro-cue and the recall task (Williams et al., 2013).

Previous VWM studies involving retro-cues mainly used three different types: the endogenous retro-cue, the exogenous retro-cue and the feature retro-cue. An endogenous retro-cue is one which is presented in the centre of the screen and points to the location of a target item (Makovski & Jiang, 2007), as described in Figure 34a. An exogenous retro-cue is one which is presented at or around the target location (Makovski & Pertzov, 2015), as described in Figure 34b. A feature retro-cue is one which tells participants one feature of the target item (Gilchrist, Duarte, & Verhaeghen, 2015). For example, as described in Figure 34c, participants receive an orientation cue of previously presented items and should then direct attention to the colour of the representation with that orientation (blue colour in this example). Participants can use these three types of retro-cues to guide their internal attention to a specific representation in VWM and then improve the allocation of VWM resources for this representation so that the cued item can receive a VWM performance advantage compared to other non-cued items. Since these three types of retro-cues direct internal attention to a specific object, I termed them *object-based retro-cues*. Thus, all of the previous hypotheses about the benefits of retro-cues were developed to account for how an object-based retro-cue can enhance VWM performance for the cued object.

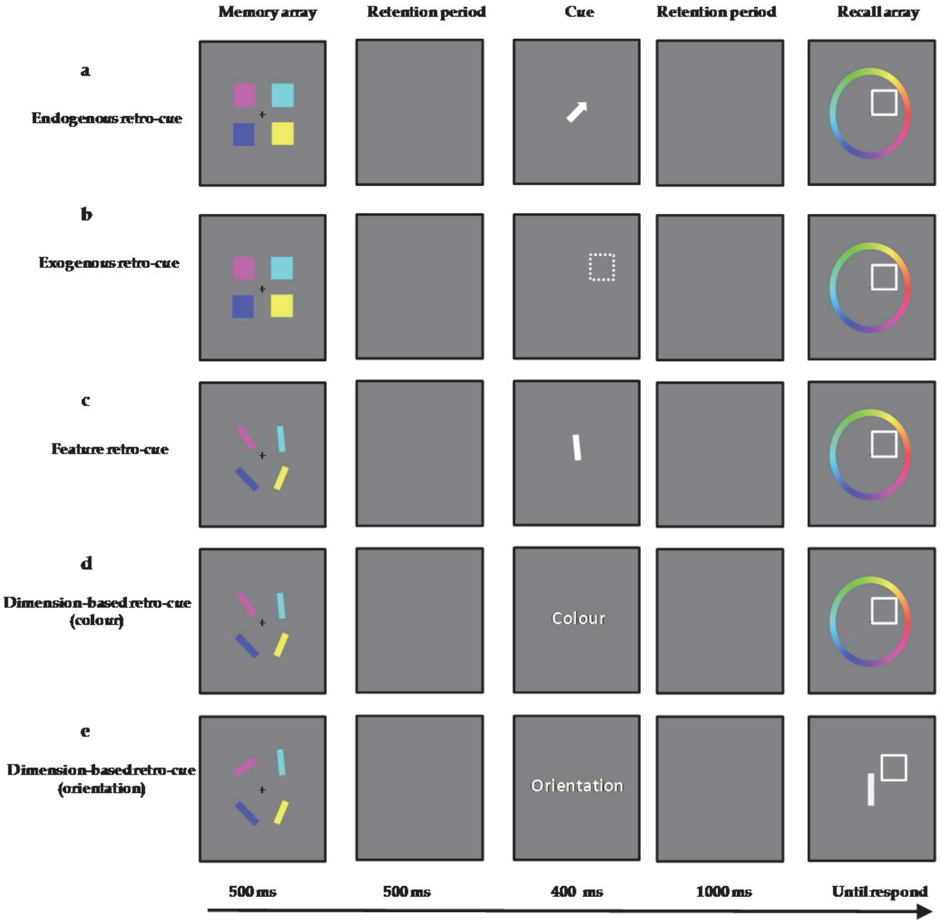

FIGURE 34. Examples of the trial schematic with (a) endogenous retro-cue, (b) exogenous retro-cue, (c) feature retro-cue, (d) dimension-based retro-cue for colour and (e) dimension-based retro-cue for orientation.

Attention can be used to select information in an object-based manner; it can also select information in a dimension-based manner. For instance, researchers have found that search performance can be improved by a valid semantic dimension-based pre-cue (Müller, Reimann, & Krummenacher, 2003). This suggests that the semantic dimension-based cue can be used to guide external attention. In addition, the effect of dimension selection of external attention on the VWM condition has also been investigated. For example, Shen, Tang, Wu, Shui and Gao (2013) asked participants to memorise information of one dimension of all the objects while ignoring information of other dimensions.

Their results suggest that even when participants use external attention to select one type of dimension, the other task-irrelevant dimensions can be consolidated into VWM automatically. This means that dimension-based external attention may not affect the allocation of VWM resources.

However, to my knowledge, although a large number of studies have focused on the influence of object-based internal attention on VWM performance, no studies have investigated the impact of dimension-based internal attention on VWM resource allocation (Souza & Oberauer, 2016). This needs to be explored since the influence mechanism regarding VWM based on dimension-based internal attention may be different from that based on object-based internal attention. Therefore, by adapting a recall task, Study VI used a dimension-based retro-cue to investigate the impact of dimension-based internal attention on VWM resource allocation.

A recall task which included a dimension-based retro-cue was used in the present study. The samples of dimension-based retro-cues are described in Figure 34d-e. The difference between dimension-based retro-cues and object-based retro-cues is that participants can use object-based retro-cues to reduce the number of memory items that must be maintained, but dimension-based retro-cues cannot be used for the same purpose. For example, participants had to memorise four items at the beginning; if an object-based retro-cue was presented after the stimulus disappeared, then the participants just needed to remember the information of the cued item, but if a dimension-based retro-cue was presented after the stimulus disappeared, then the participants still needed to maintain information on the four items.

If participants can use their dimension-based internal attention to adjust VWM resource allocation, then a benefit of the dimension-based retro-cue should be evident. In contrast, if dimension-based internal attention, like dimension-based external attention, does not affect VWM resource allocation, then participants would not gain any benefit from the dimension-based retro-cue.

7.2 Experiment 12 - Benefit of dimension-based retro-cues in VWM

7.2.1 Methods

There were two sessions in Experiment 12: In the first session, participants were asked to perform colour and orientation single dimension recall tasks. In 50% of trials, there was a dimension-based retro-cue (for instance, in the colour recall task, only the cue ‘colour’ would appear at the centre of the screen during the blank interval), while no cue was provided in the other 50% of trials. By comparing cued to un-cued conditions, the results should indicate whether cue words influence recall performance. In the second session, participants were asked to perform a double dimension recall task, for which 50% of the trials had a dimension-based retro-cue while the remainder did not. Via this task, the results should show whether benefits of dimension-based retro-cues exist by comparing these two conditions.

Participants

A total of 20 participants (18 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

Participants viewed the display at a distance of 60 cm, and the stimuli were presented on a 19-inch LCD monitor (1280×1024 pixel) in a dark room. The four coloured bars (1.1°×0.4º) of the memory array were presented in four possible positions. The orientation and colour of each coloured bar were randomly selected from 180 possible angles and 360 possible colours. The dimension cue stimuli (3.2°×1.5°) were the words 'orientation' or 'colour' presented at the centre of the screen.

Procedure

The experiment included two sessions. In the first session, participants completed two single dimension recall tasks. After the completion of single dimension recall tasks and a rest period of at least five minutes, the participants completed the second session, consisting of a double dimension recall task.

The first session tasks consisted of a colour recall block and an orientation recall block. Participants were asked to perform two single dimension recall tasks with the trial structures depicted in Figure 35a. In these blocks, the memory array items were identical and only the instructions of which dimension were relevant (memorise four colours and recall one of them, in the colour recall block; memorise four orientations and recall one of them, in the orientation recall block). In each block, one-half of the trials included a dimension-based retro-cue ('colour' or 'orientation') during the retention period, which were randomly interleaved with no cue trials. Each trial began with a 300-ms fixation dot presented at the centre of the screen. Each memory array containing four coloured bars was then presented for 500 ms, followed by a 1700-ms blank retention period. On cued trials, and after 500 ms had elapsed from the disappearance of the memory array, the dimension-based retro-cue (100% valid) appeared for a duration of 400 ms. The retro-cue was then followed by the remainder of the retention interval, which lasted 800 ms. On no-cued trials, the screen remained blank during the entire 1700-ms retention period. After the retention period, a white square outline was presented at one memory stimuli location. In the colour recall condition, a response wheel was presented at the centre of the screen and consisted of 360 coloured segments corresponding to possible stimulus colours. Participants had to report the colour of the cued item. In the orientation recall condition, an adjustable white bar was presented at the centre of the screen. Participants had to adjust the orientation of the probe bar to match that of the cued bar. Participants were told that they could continue adjusting it until they felt satisfied. After they had finalised their responses, feedback on response offset was presented on the screen.

In the second session, participants were asked to perform a double dimension recall task, which comprised a mixed version of the colour and orientation recall tasks in the first session. The procedure for the double dimension recall task was identical to that for the recall tasks in the first session, except that participants were instructed to memorise both the colour and orientation of the bars, and the type of test array was selected at random on each trial. Dimension-based retro-cue type (cue, no-cue) and test type (colour, orientation) were manipulated among participants (Figure 35b).

In the first session, the order of the colour recall block and orientation recall block was counterbalanced across participants. Each dimension-based retro-cue type (cued, no-cued) had 50 trials, with a total of 100 trials per recall block. In the second session, there were 50 trials for each condition (cued-colour, no-cued-colour, cued-orientation, no-cued-orientation), with a total of 200 trials. Trials were fully randomised. Before the experiment started, participants practised for at least 16 trials to ensure they understood the procedures.

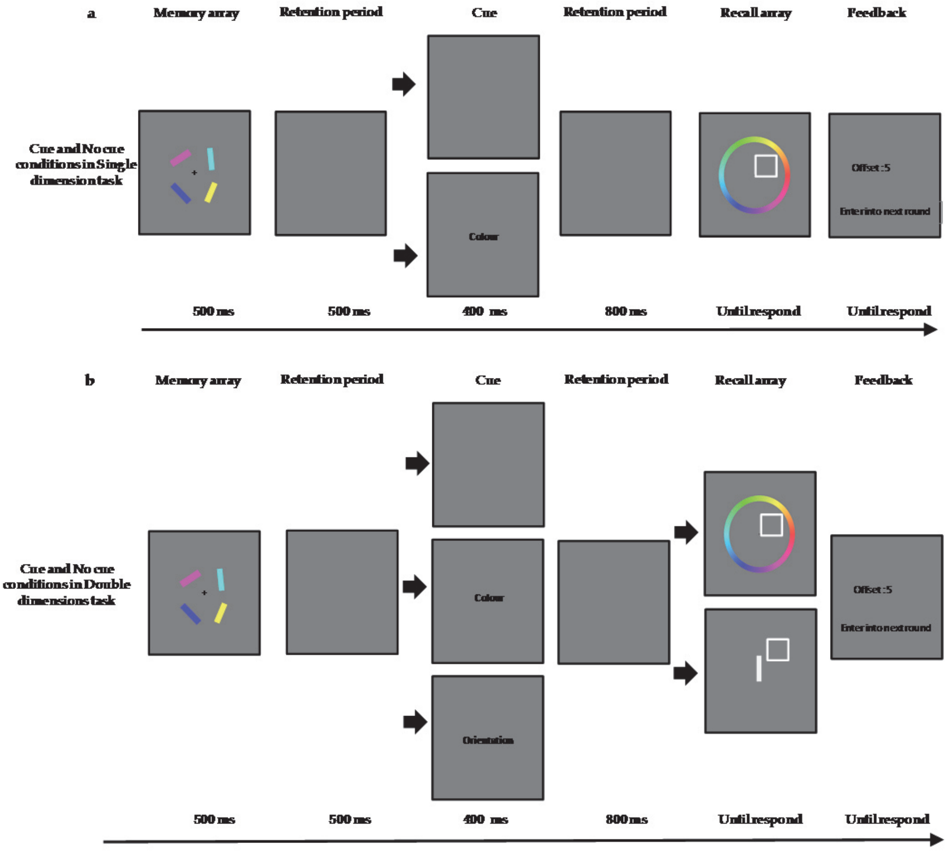

FIGURE 35. Trial schematic of (a) the first session (only the colour recall block is depicted) and (b) second session in Experiment 12.

Data analysis

Similar to Experiments 5–11, the offset value for each participant and each condition (cue and no-cue condition for the first session; cued-colour, no-cued-colour, cued-orientation and no-cued-orientation for the second session) was calculated.

For the double dimension block, a retro-dimension benefit index (RDEI) was calculated based on the offset values, which was defined as

$$RDEI = \frac{Offset(nocue) - Offset(cue)}{Offset(nocue)}$$

RDEI thus represents the relative improvement between dimension-based retro-cue and no-cue conditions.

7.2.2 Results and discussion

For the colour recall task, the offset for the cue condition was marginally higher than that for the no-cue condition [$t(19) = 1.936$, $p = .068$]; for the orientation recall task, similarly, the offset was marginally higher for the cue condition than for the no-cue condition [$t(19) = 1.878$, $p = .076$] (Figure 36). These results suggest that recall performance is slightly worse after a retro-cue. Namely, the appearance of the dimension cue words may have had a small negative effect on the performance of the recall task.

For the double dimension task, the offsets were lower for the cue condition than for the no-cue condition, for both colour recall trials [$t(19) = 3.055$, $p < .01$] and orientation recall trials [$t(19) = 2.218$, $p < .05$]. The mean RDEI of colour was 12.8%, which was significantly higher than zero [$t(19) = 2.701$, $p < .05$], while the mean RDEI of orientation was 4.8%, which was marginally higher than zero [$t(19) = 1.945$, $p = .067$]. The results indicate that the appearance of the dimension-based retro-cue can improve performance in the recall task.

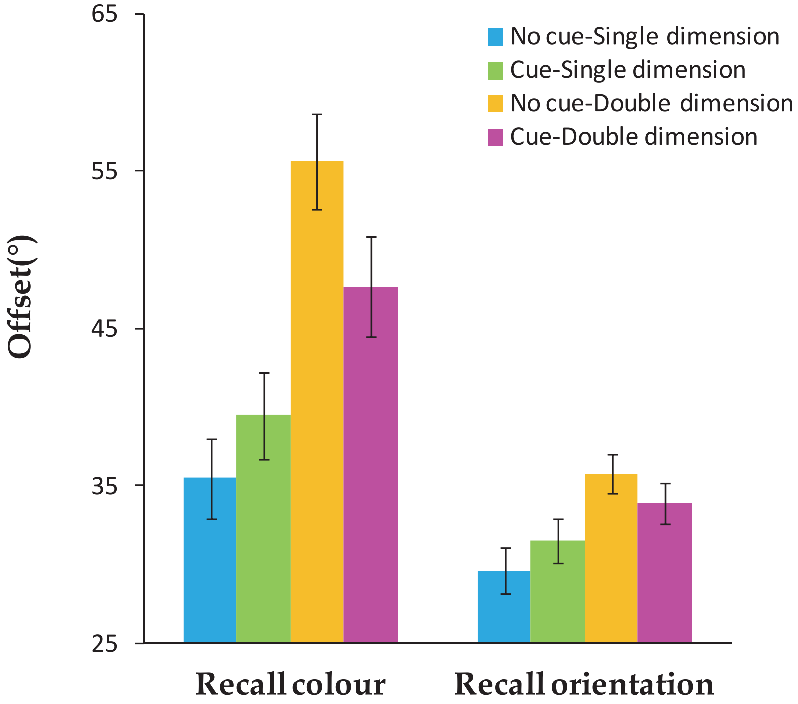

FIGURE 36. The offset results of the no cue-single dimension, cue-single dimension, no cue-double dimension and cue-double dimension conditions in Experiment 12. Error bars represent the standard error of the mean.

In the first session, a marginally significant difference was found, suggesting that the appearance of the dimension cue words could slightly impair recall performance. These results demonstrate that the visual input of the cue appears to have a negative impact on performance.

The results of the second session were completely contrary to those of the first session. The cue improved recall performance rather than hurting it. These results suggest that the dimension-based retro-cue not only offsets the interference caused by the appearance of the cue (as observed in session 1) but also provides an additional benefit to VWM maintenance.

To my knowledge, most previous research has used a retro-cue to point to one object, such that participants could use object-based internal attention to allocate more VWM resources to a target item, thus improving the memory maintenance of the target (Souza, Rerko, Lin, & Oberauer, 2014). If the sole benefit of a dimension-based retro-cue was increased VWM resources allocated to a given retro-cued item, then the present results would not be expected. In Experiment 12, after participants received a dimension-based retro-cue, they still needed to maintain the same number of objects in VWM rather than prioritising a single item. This is interesting because the present results could not be easily explained by previous accounts of the mechanism of the benefit of the object-based retro-cue. That is, the present results extend the phenomenon to a dimension-based retro-cue benefit. Another advantage of using a recall task is that the model fitting can be used to separate guess rate, non-target reported rate and memory precision with the swap model (Bays et al., 2009). The improvement in behavioural performance may be caused by an increase in VWM precision, a decline in non-target reported rate or a decline in the guess rate. Thus, using the swap model could further unpack the sources of retro-dimension benefit. However, because Experiment 12 did not have a sufficient number of trials in the recall task to reliably implement swap model fitting (i.e., there would be too much error in the fit), the experimental design was adjusted in Experiment 13 to accommodate swap model fitting. Thus, in the next experiment, the retro-dimension benefit was examined with a memory rate index and a memory precision index.

7.3 Experiment 13 - Source of dimension-based retro-cue benefit

7.3.1 Methods

In Experiment 13, a replication of Experiment 12 was conducted in order to observe whether the effects of Experiment 12 were reliable. However, the latter experiment was extended to determine the source of the dimension effect's benefit by using the swap model to calculate the probability of guessing, non-target reporting and VWM precision in Experiment 13.

Participants

A total of 20 new participants (18 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

The stimuli used in Experiment 13 were identical to those used in Experiment 12.

Procedure

The design and procedure in Experiment 13 were identical to those in Experiment 12, except for the following changes: (1) Reduced memory load. The total number of items in the memory array was reduced from four to three. In each trial, three coloured bars were presented in three randomly chosen locations out of the four possible locations; (2) Increased differences between each memory stimulus. The minimum difference in colour and orientation between each coloured bar was increased to 30 orientation degrees and 60 colour steps; (3) Replaced the no-cue condition with a neutral cue condition. In neutral cue conditions, the cue word for 'random' was presented at the centre of the screen during the dimension-based retro-cue period; (4) Increased time to use dimension-based retro-cue. Timing of the inter-stimulus interval (ISI) between the dimension-based retro-cue and the recall array was increased from 800 ms to 1300 ms; (5) Adjusted number of trials in each block. The colour and orientation recall blocks in the first session of Experiment 12 were changed to practice blocks in Experiment 13; the trials of each block were reduced from 100 to 48 (24 trials for the dimension condition and the neutral cue condition separately); the order of these practice blocks was still counterbalanced across participants. In the second session, the trials of the double dimension recall task were increased from 200 to 400, so that there were 100 trials for each condition (valid cue-colour, neutral cue-colour, valid cue-orientation, neutral cue-orientation). The trial structures are depicted in Figure 37.

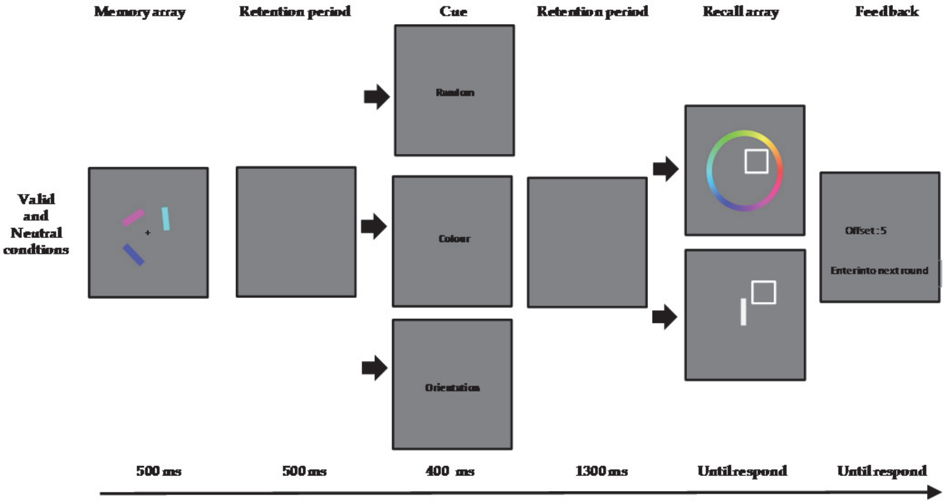

FIGURE 37. Trial schematic of the valid cue and neutral cue conditions in Experiment 13.

Data analysis

The offset value was calculated as in Experiment 12. The RDEI was calculated as the relative improvement between the valid and neutral conditions. For obtaining the VWM number index and precision index, the offset data were fitted with the swap model (Bays et al., 2009). Three independent parameters were determined by maximum likelihood estimation: the guess rate (P_g), non-target reported rate (P_b) and precision index (SD).

7.3.2 Results and discussion

In the colour recall trials, the offsets in the neutral cue condition were larger than those in the valid cue condition [$t(19) = 5.402$, $p < .001$]. The mean RDEI was 17.5%, which was significantly greater than zero [$t(19) = 6.258$, $p < .001$]. In the orientation recall trials, the neutral cue condition was larger than that in the valid cue condition [$t(19) = 6.017$, $p < .001$]. The mean RDEI was 16.2%, which was significantly greater than zero [$t(19) = 7.484$, $p < .001$] (Figure 38). These results were in line with those in Experiment 12.

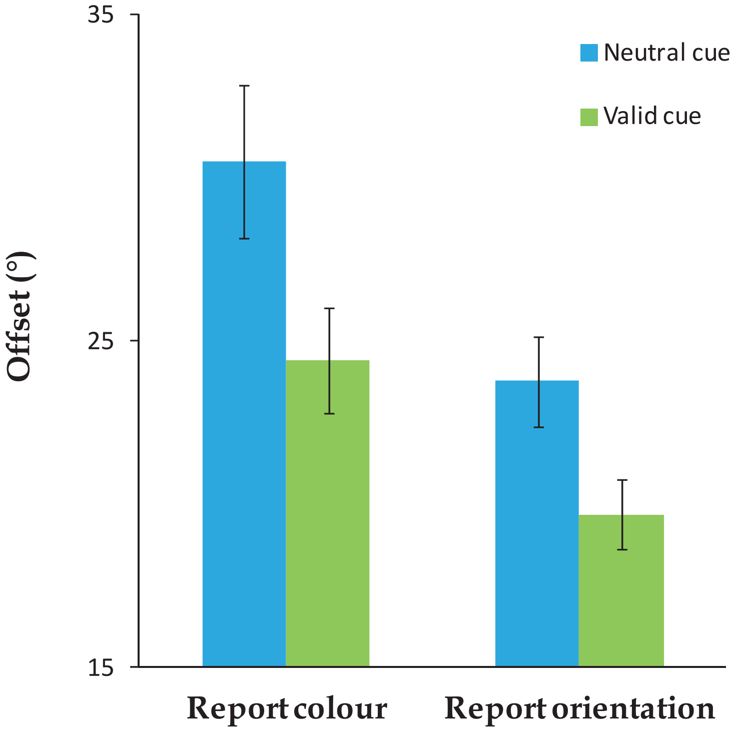

FIGURE 38. The offset results of the neutral cue and valid cue conditions in Experiment 13. Error bars represent the standard error of the mean.

In colour recall trials, the precision parameter (SD) in the valid cue condition was not significantly different from that in the neutral cue condition [$t(19) = 0.248$, $p = .807$]. The non-target reported rate (P_b) in the valid cue condition was not significantly different from that in the neutral cue condition [$t(19) = 1.131$, $p = .272$]. The guess rate (P_g) in the valid cue condition was significantly lower than that in the neutral cue condition [$t(19) = 2.206$, $p < .05$]. In the orientation recall trials, the precision parameter (SD) in the valid cue condition was not significantly different from that in the neutral cue condition [$t(19) = 1.261$, $p = .223$]. The non-target reported rate (P_b) in the valid cue condition was not significantly different from that in the neutral cue condition [$t(19) = 1.244$, $p = .229$]. The guess rate (P_g) in the valid cue condition was significantly lower than that in the neutral cue condition [$t(19) = 2.383$, $p < .05$] (Figure 39). The results show that the presentation of the dimension cue can only lead to a lower guess rate; it does not affect VWM precision or the non-target reported rate.

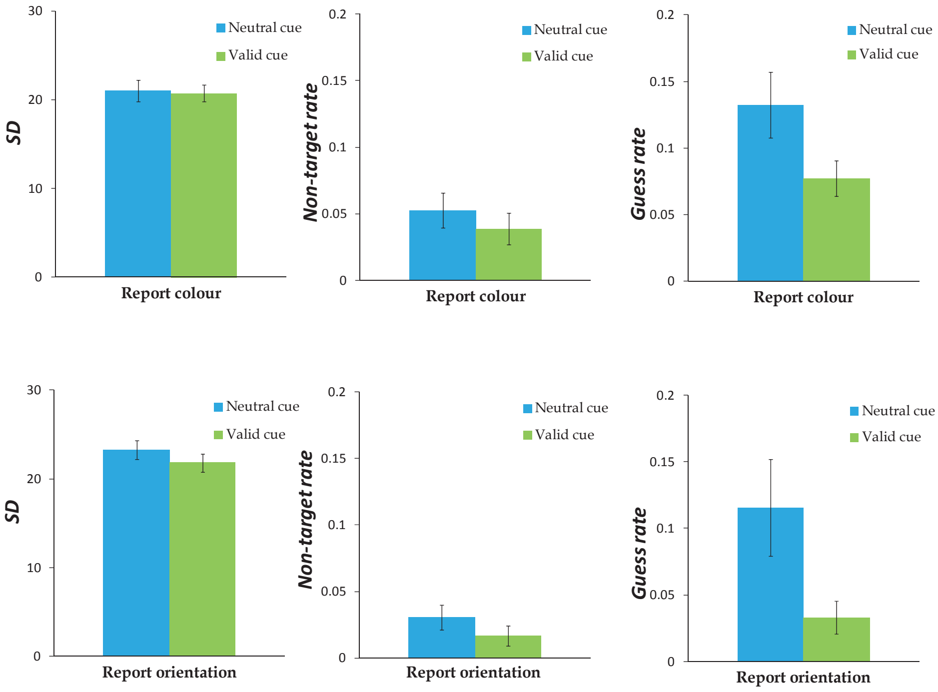

FIGURE 39. The P_g, P_b and SD results of neutral cue and valid cue conditions in Experiment 13. Error bars represent the standard error of the mean.

Experiment 13 replicated the results of Experiment 12. The findings indicate that the dimension-based retro-cue benefit is a stable effect. In addition, the results suggest that the source of the dimension-based retro-cue benefit is not an increase in memory precision or a decline in the non-target reported rate but is instead due to a decline in the guess rate. These results are similar to those of previous studies of object-based retro-cue benefit, in which the authors suggested that changes in attention to one object could decrease the guess rate but could not enhance memory precision (Murray, Nobre, Clark, Cravo, & Stokes, 2013; Souza et al., 2014). The mechanisms of the dimension-based retro-cue benefit are explored further in Experiment 14. In sum, the results show that the appearance of the dimension-based retro-cue leads to a lower guess rate but does not influence the non-target reported rate or memory precision. Thus, the results of Experiments 12 and 13 suggest that as a top-down retro-cue, dimension-based retro-cues can benefit performance.

Because the benefit of dimension-based retro-cues was a novel finding, Experiment 14 was conducted to replicate the results and further explore the mechanisms of this benefit.

7.4 Experiment 14 - Impact of delay on dimension-based retro-cue benefit

Two aims were included in Experiment 14. The first aim was to replicate the dimension-based retro-cue benefit observed in Experiment 13. More importantly, the second aim was to test whether the dimension-based retro-cue benefit was caused by protecting the cued dimension information from degradation over time (Matsukura, Luck, & Vecera, 2007; Pertzov, Bays, Joseph, & Husain, 2013). In other words, during VWM maintenance, the cued dimension of representations might be unaffected by temporal decay, which dramatically degrades the non-cued dimension information of representations. The procedures in Experiment 14 were similar to those in Experiment 13, with the exception that short-delay neutral conditions were added to compare them with the normal-delay neutral conditions. In the normal-delay neutral conditions, the recall array was presented 1300 ms after the neutral retro-cue disappeared. In the short-delay neutral conditions, the recall array was presented only 50 ms after the neutral retro-cue disappeared. This manipulation tested whether there was a degradation effect in the recall task in this experimental setup. If no performance difference between the normal-delay neutral and short-delay neutral conditions was observed, this would suggest that no degradation effect existed in the present experimental task. This would rule out the possibility that protection from degradation is a potential mechanism underlying the dimension-based retro-cue benefit. In contrast, if there was a degradation effect, performance would be worse in the normal-delay neutral condition than in the short-delay neutral condition.

7.4.1 Methods

Participants

A total of 28 new participants (26 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

The stimuli used in Experiment 14 were identical to those used in Experiments 12 and 13.

Procedure

The design and procedure of Experiment 14 were identical to those of Experiment 13, except for the following changes: (1) Added two short-delay neutral conditions (one for colour condition, the other for orientation condition). The procedure for short-delay neutral conditions in Experiment 14 was similar to that for the neutral conditions in Experiment 13, except that the duration of the retention period between the neutral cue and the test array was reduced from 1300 ms to 50 ms; (2) Reduced the number of trials. In each condition, the number of trials was reduced from 100 to 50 so that there was a total of 300 trials for six conditions. The trial structures are depicted in Figure 40. The conditions were intermixed within the experiment. Before the experiment started, participants practised for at least 16 trials to ensure they understood the procedures.

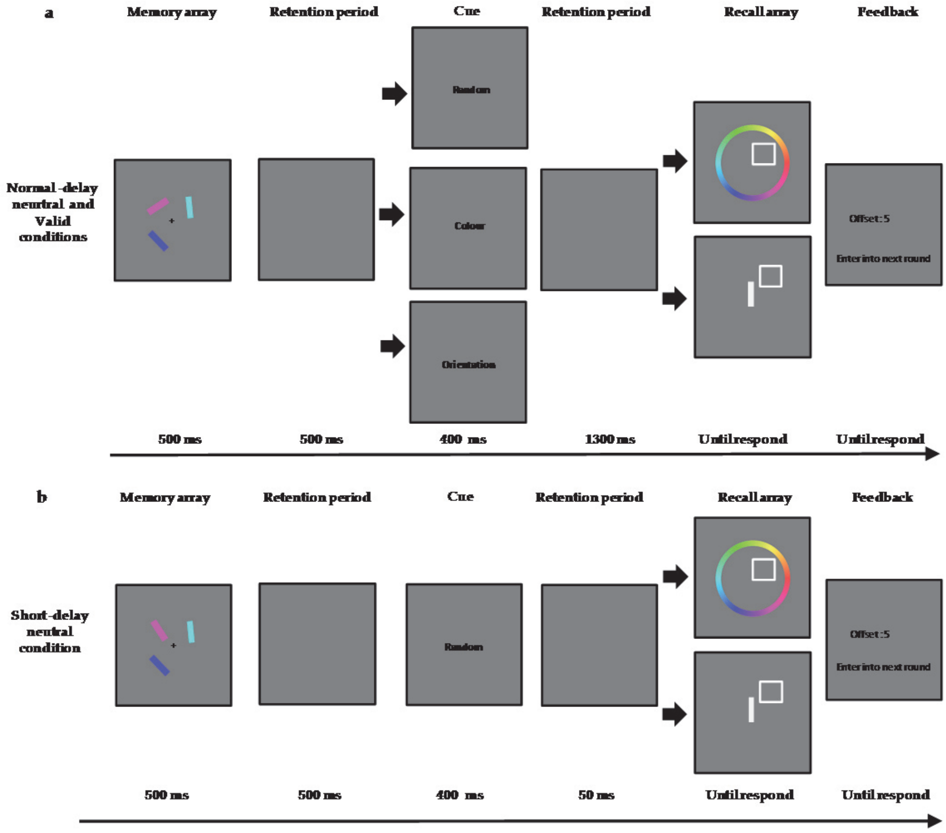

FIGURE 40. Trial schematic of the (a) valid cue, neutral cue and (b) short-delay neutral cue conditions in Experiment 14.

Data analysis

The data analysis steps in Experiment 14 were identical to those in Experiments 12 and 13. Because of the reduction in the number of trials, model fitting was not used in this experiment.

7.4.2 Results and discussion

A one-way ANOVA with a display condition (valid vs. short-delay neutral vs. normal-delay neutral) for the offsets in the colour recall trials was conducted.

There was a significant main effect of display conditions [*F*(2,54) = 32.030, *p* < .001]. Planned comparisons showed that the offset in the short-delay neutral condition was not significantly different from that in the normal-delay neutral condition [*t*(27) = 1.628, *p* = .115]. The offsets in the valid condition were significantly smaller than those in the short-delay neutral condition [*t*(27) = 7.188, *p* < .001] and the normal-delay neutral condition [*t*(27) = 5.410, *p* < .001]. The mean RDEI was 23.6%, which was significantly greater than zero [*t*(27) = 5.095, *p* < .001]. In the orientation recall trials, a one-way ANOVA with a display condition (valid vs. short-delay neutral vs. normal-delay neutral) for the offsets was conducted. There was a significant main effect of display conditions [*F*(2,54) = 11.201, *p* < .001]. Planned comparisons showed that the offset in the short-delay neutral was not significantly different from that in the normal-delay neutral condition [*t*(27) = 1.328, *p* = .195]. The offsets in the valid condition were significantly smaller than those in the short-delay neutral condition [*t*(27) = 3.478, *p* = .002] and the normal-delay neutral condition [*t*(27) = 4.482, *p* < .001]. The mean RDEI was 15.1%, which was significantly greater than zero [*t*(27) = 4.680, *p* < .001] (Figure 41).

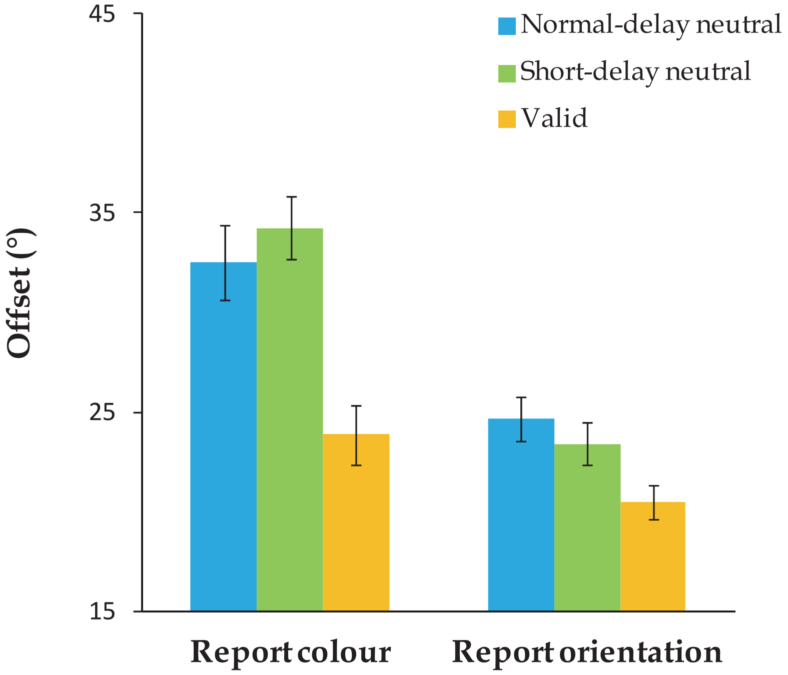

FIGURE 41. The offset results of the normal-delay neutral cue, short-delay neutral cue and valid cue conditions in Experiment 14. Error bars represent the standard error of the mean.

Experiment 14 replicated the observed benefit of a dimension-based retro-cue. The results further suggest that after the neutral cue disappears, the length of the blank interval has no impact on recall performance. This finding indicates that VWM representations did not degrade during the retention period in the present task. Since there was no memory degradation during the blank interval, the dimension-based retro-cue benefit should not be simply interpreted as a protective mechanism for the cued dimension information against memory degradation.

7.5 Experiment 15 - Dimension-based retro-cue benefit under low memory load

By measuring the memory ability of 170 students, Vogel and Awh (2008) determined that the average capacity of VWM was about 2.9. Thus, the memory set size of four in Experiment 12 and three in Experiments 13 and 14 might be considered a high memory load for some participants. In addition, Lavie, Hirst, de Fockert and Viding (2004) proposed that an active mechanism of attentional control could be used for rejecting non-target information. But the capacity to engage in active control is weakened under high memory load, resulting in increased processing of non-target information during the response phase. Thus, when the memory load potentially exceeds average capacity (i.e., Experiment 13 and 14), participants might be disturbed by the information from a non-cued dimension in the neutral condition, and the dimension-based retro-cue can be used to resist this interference by suppressing or removing non-cued dimension information in advance. If this is the true mechanism of dimension-based retro-cue benefit, then when the memory load is low, the ability to reject information from the non-cued dimension should be strengthened even in the neutral condition, which would lead to a corresponding reduction of the dimension-based retro-cue benefit. Thus, Experiment 15 was conducted with a reduced set size of items and tested whether the dimension-based retro-cue benefit disappeared when the set size was low. The short-delay neutral conditions were reserved, as in Experiment 14, to replicate the lack of degradation effect under low VWM load.

7.5.1 Methods

Participants

A total of 24 new participants (17 females) were recruited from the participant pool at Minnan Normal University. They reported normal or corrected-to-normal vision and no history of neurological problems. All participants gave informed consent according to procedures approved by the ethics committee of Minnan Normal University.

Stimuli

The stimuli used in Experiment 15 were identical to those used in Experiments 12, 13 and 14.

Procedure

The procedures in Experiment 15 were identical to those in Experiment 14, except that the memory set size in the memory array was reduced from three to two. The colour bars in the memory array were presented in two random locations of the four possible locations (Figure 42).

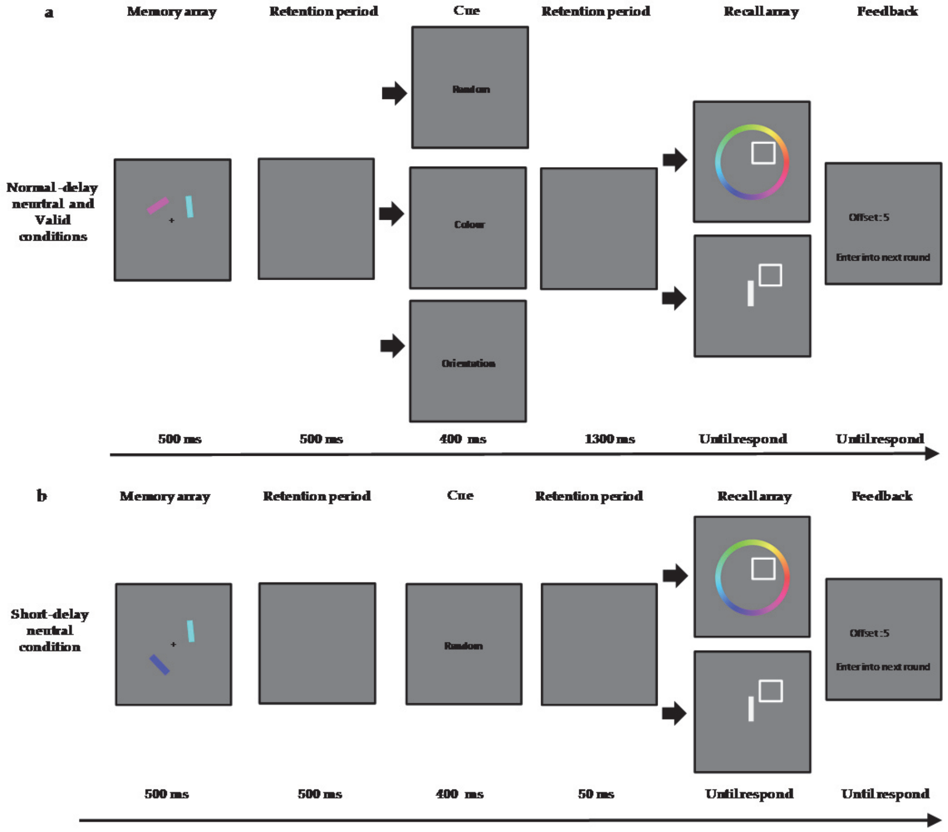

FIGURE 42. Trial schematic of the (a) valid cue, neutral cue and (b) short-delay neutral cue conditions in Experiment 15.

Data analysis

The data analysis steps for Experiment 15 were identical to those for Experiment 14.

7.5.2 Results and discussion

A one-way ANOVA with a display condition (valid vs. short-delay neutral vs. normal-delay neutral) for the offsets in the colour recall trials was conducted. There was a significant main effect of display conditions [$F(2,46) = 8.548$, $p < .001$]. Planned comparisons showed that the offset in the short-delay neutral condition was not significantly different from that in the normal-delay neutral condition [$t(23) = 0.028$, $p = .978$]. The offsets in the valid condition were significantly smaller than those in the short-delay neutral condition [$t(23) = 3.556$, $p < .01$] and normal-delay neutral condition [$t(23) = 3.312$, $p < .01$]. The mean RDEI was 16.5%, which was significantly greater than zero [$t(23) = 2.686$, $p < .05$]. In the orientation recall trials, a one-way ANOVA with a display condition (valid vs. short-delay neutral vs. normal-delay neutral) for the offsets was conducted. There was a significant main effect of display conditions [$F(2,46) = 20.189$, $p < .001$]. Planned comparisons showed that the offset in the short-delay neutral condition was not significantly different from that in the normal-delay neutral condition [$t(23) = 0.991$, $p = .332$]. The offsets in the valid condition were significantly smaller than those in the short-delay neutral condition [$t(23) = 5.438$, $p < .001$] and the normal-delay neutral condition [$t(23) = 4.589$, $p < .001$]. The mean RDEI was 16%, which was significantly greater than zero [$t(23) = 4.083$, $p < .001$] (Figure 43). The results of Experiment 15 were in line with those of Experiment 14.

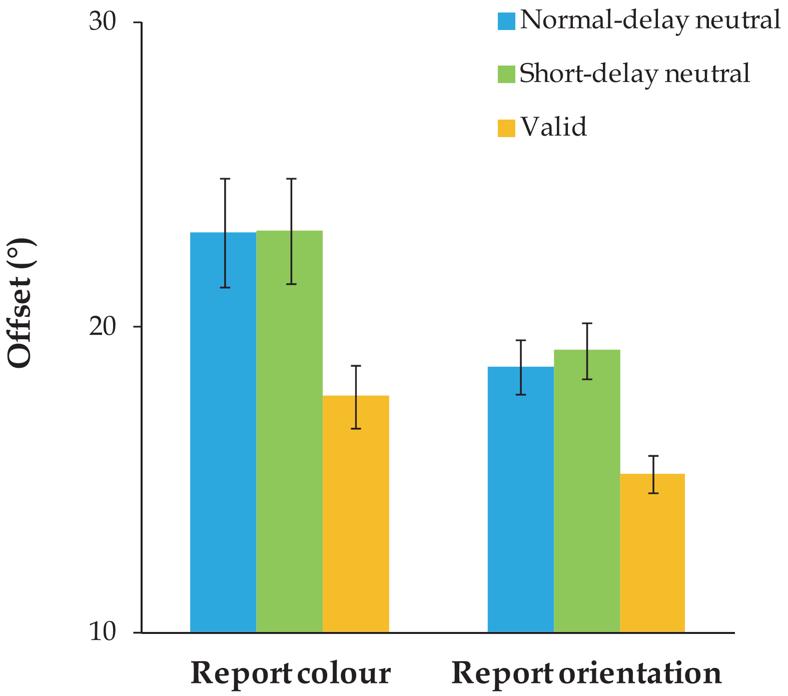

FIGURE 43. The offset results of the normal-delay neutral cue, short-delay neutral cue and valid cue conditions in Experiment 15. Error bars represent the standard error of the mean.

In addition to replicating the null effect of retention interval, ruling out the degradation protection mechanism, the results of Experiment 15 suggest that the dimension-based retro-cue benefit was robust at a low memory load, such that no reduction of the dimension-based retro-cue benefit was observed compared to Experiment 14. These results demonstrate that the mechanism of the dimension-based retro-cue benefit could not be simply explained as participants using the dimension-based retro-cue to reduce interference from processing the non-cued dimension information.

7.6 Discussion of Study VI

In Experiment 12, better behavioural performance was found in the cue condition compared to the no-cue condition. In Experiment 13, although there was no significant difference between the valid cue and neutral cue conditions for both the non-target reported rate and memory precision, the guess rate in the valid cue condition was significantly lower than that in the neutral cue condition. In Experiments 14 and 15, although no significant difference was found between the short-delay neutral cue and neutral cue conditions, better performance was found in the valid cue condition than in the short-delay neutral cue and normal-delay neutral cue conditions. These results suggest that there is a stable dimension-based retro-cue benefit by which participants could use a dimension-based retro-cue to improve performance regarding the specified dimension during the maintenance process. Recently, the same effect has been confirmed by a follow-up study (Niklaus, Nobre, & van Ede, 2017).

One innovation of the present study was that a dimensional semantic word cue was used as the retro-cue. Using cue words is a typical approach when researchers investigate whether knowledge of a dimension of an upcoming target will influence attention. For example, Müller et al. (2003) investigated the issue by presenting a symbolic cue, the words ‘colour’, ‘orientation’ or ‘neutral’, to participants before a pop-out search task. Their results demonstrated that participants could use top-down control to bias their attentional weight to a task-relevant dimension based on the cue word. Further, there are a few retro-cue effect studies which presented a symbolic cue word as the object-based retro-cue, such as the words ‘red’, ‘circle’ or ‘wait’ in Gilchrist et al.’s (2015) study, and the words ‘red’, ‘green’ or ‘all’ in Hollingworth and Maxcey-Richard’s (2013) study. The present results show that dimensional cue words can elicit a dimension-based retro-cue benefit, which is consistent with prior work demonstrating that a semantic word cue is effective. Further, using semantic cue words provided an additional source of experimental control since they minimised the visual difference between valid and neutral cues (i.e., both were words).

Importantly, the results suggest that the mechanism of dimension-based retro-cue benefit is different from the mechanism of object-based retro-cue benefit. In previous studies of the retro-cue task, participants could use the object-based retro-cue to narrow the scope of attention to one specific target item and change cognitive resource allocation to the memory items (for instance, participants needed to focus on four items at the beginning, but only on one item after the retro-cue). However, in the current study, participants could not use the dimension-based retro-cue to narrow the scope of attention to a single item (after participants saw the cue, they still needed to focus on all memory items), but they could use the cue to change the cognitive resource allocation to target one dimension of all items. The evidence of a dimension-based retro-cue benefit reported here extends the literature on top-down control of resources during VWM maintenance and fills critical gaps in the literature regarding the impact of internal attention on VWM representations.

In addition, the results of Experiments 14 and 15 show that the length of the blank interval does not influence recall performance. A similar result was observed in Souza et al.'s (2014) study. They asked participants to perform a recall task with an object-based retro-cue (pointing to only one item). In their no-delay condition, the cue and test array appeared at the same time, 1000 ms after the visual stimulus offset. In the delay condition, the retro-cue appeared 1000 ms after the visual stimulus offset, and the test array appeared 2000 ms after the visual stimulus offset. Although the participants needed to maintain the VWM representations for a longer time in the delay condition (1000 ms in the no-delay condition, 2000 ms in the delay condition), they achieved better performance in the delay condition than in the no-delay condition. These results imply that after participants received the cue, they needed some time to use attention to change the cognitive resource allocation, or else the appearance of the test array would interfere with the resource reallocation process. Unlike the change detection task, in the recall task used here, there were no new visual items covering the location of memory items when the recall array appeared. Thus, the interference caused by the recall array was not simply due to new visual information input. Accordingly, the interference might have been due to the cue and recall array appearing at the same time. This would result in the resource reallocation process, which is triggered by the cue, and the decision-making process, which is triggered by the recall array, to compete for cognitive resources, thus reducing performance on the recall task. Therefore, the appearance of the retro-cue before the recall array can separate the resource reallocation process and decision-making process, avoiding cognitive interference from the recall array. This suggestion can explain why, in Experiments 14 and 15, behavioural performance was better in the valid cue condition than in the short-delay neutral cue condition. Thus, I suggest that the dimension-based retro-cue benefit was caused by enhancement of the target dimension, forgetting the non-target dimension and separating the resource reallocation process and decision-making process. This makes the paradigm in Study VI well suited for future researchers interested in exploring the mechanisms of dimension-based retro-cue benefit.

In Experiment 13, no memory precision difference was found across conditions, but a lower guess rate in the valid cue condition than in the neutral cue condition was demonstrated. The results show that the improvement in performance as a function of dimension-based retro-cues is reflected in an increased probability of reporting the target, but not in the probability of reporting the non-target or the precision with which this item is remembered.

In summary, the results show a stable dimension-based retro-cue benefit. The dimension-based internal attention can be used to allocate VWM resources to a particular dimension of representation. The contaminant of high memory load has been ruled out, and the possibility that the benefit is caused by protection from degradation has been rejected. The results further support the notion that visual features could be independent and stored separately from each other, such that objects have multiple feature levels of representation in VWM. More details can be found in 8.4.

8 GENERAL DISCUSSION

8.1 Consolidation manners for different materials

In Study I, for the first time, the CDA was used to measure the bandwidth of consolidation. The results suggest distinct patterns for consolidating colour and orientation information.

Previous results suggest that the consolidation manner for orientation information can be parallel (Rideaux et al., 2015; Rideaux & Edwards, 2016). The CDA results of Study I cast further doubt on the notion that all features could be consolidated in parallel, as differences were found in CDA patterns between colour and orientation materials: While the colour pattern was consistent with the parallel consolidation manner, the orientation pattern was consistent with the serial consolidation manner. Thus, Study I provides convergent evidence that the consolidation manner depends on the memory materials. Even so, it should be noted that Rideaux et al. (2015) used behavioural experiments to provide evidence that motion direction can also be consolidated in parallel. However, motion direction has not been examined in the present research, and it is quite possible that motion direction may be consolidated via a parallel mechanism. Thus, it would be interesting to examine consolidation limits of motion direction in future studies using electrophysiological measures. The findings of Study I can be used to conclude that the bandwidth for consolidation is determined by the stimulus feature.

8.2 Two-phase resource allocation model in VWM

Previous studies have suggested that there are two possibilities for how VWM resources are allocated to store items (Machizawa et al., 2012; Murray et al., 2012). Allocation may be based on the number of items via stimulus-driven factors, or it may be based on the task demands via voluntary control. Based on the results of Study II, III and IV, here I propose that VWM resource allocation is a hybrid of involuntary and voluntary processes, with voluntary allocation occurring after involuntary allocation. In the involuntary phase, participants must first consolidate each item by allocating a small amount of resources to create some low-precision representations. Only after the completion of this involuntary phase can they reallocate the resources voluntarily according to the task demand. From a cognitive processing point of view, voluntary allocation requires top-down control, which presumably takes extra processing time. In studies of selective attention, for example, it is known that it takes more time to deploy top-down attention than bottom-up attention (Jonides, 1981; Liu, Stevens, & Carrasco, 2007; Muller & Rabbitt, 1989; Pinto, van der Leij, Sligte, Lamme, & Scholte, 2013). From an information theoretical point of view, the involuntary phase can maximise the storage of information with little cost of control, thus providing an efficient mechanism for consolidation. From an ecological point of view, this arrangement also makes sense. When individuals first encounter a visual scene, it seems beneficial to sample as much information as possible to detect potentially important objects. An automatic, involuntary process would be suitable for such a sampling purpose. This view is in line with Liesefeld, Liesefeld and Zimmer's (2014) findings that participants must first process all items to a certain degree before they can determine whether any irrelevant items are present. Interestingly, a recent study proposed that when a new item is encountered in the environment, it can gain access to VWM automatically without the need for executive resources (Allen, Baddeley, & Hitch, 2014), thus also lending support to the current proposal of the involuntary phase.

After the completion of this involuntary phase, participants should be able to consolidate more visual information for readjusting resource allocation according to task demands. Such reallocation requires participants to either use free resources (if available at the end of the involuntary phase) or release some resources for reallocation among items (when all the resources have been used at the end of the involuntary phase). In both cases, memory precision for items that are represented by more resources will be improved. Furthermore, this kind of storage likely needs to acquire new information from either the physical stimuli or their visible persistence, as simply duplicating information by existing representations should not increase the informational content, hence the precision, of the memory. Because visible persistence decays rapidly over time, voluntary allocation would need longer stimulus duration than involuntary allocation. Thus, stimulus duration has been manipulated in Study III and the findings could be interpreted in terms of consolidation of VWM representation.

Therefore, I propose a two-phase VWM resource allocation model that can explain the two different patterns of previous results (Gao et al., 2011; Machizawa et al., 2012; Murray et al., 2012; Zhang & Luck, 2011). The model states that the VWM resource could be allocated only by stimulus-driven factors in the early phase. However, after the completion of the early phase, allocation can enter the late phase, where it can be flexibly and voluntarily controlled according to task demands. In other words, individuals automatically allocate VWM resources in the early phase and create a low-precision representation for each item that needs to be remembered. After the low-precision representations have been fully created or the VWM resources have been completely allocated, the individual can reallocate VWM resources and create high-precision representations according to the requirements of the task. Therefore, for a given set size, it takes a certain amount of encoding time for an individual to control attention to adjust the VWM resources to trade-off between VWM number and precision in the VWM task without distractors.

Most previous results in studies of voluntary trade-off between VWM number and precision can be predicted by the two-phase model. Table 1 summarises stimulus and result patterns found in eight published papers in the literature about the voluntary trade-off between VWM number and precision (Bocincova, van Lamsweerde, & Johnson, 2017; Fougnie, Cormiea, Kanabar, & Alvarez, 2016; Gao et al., 2011; Machizawa et al., 2012; Murray et al., 2012; Ye et al., 2017; Ye, Zhang, Liu, Li, & Liu, 2014; Zhang & Luck, 2011). The table also reports whether these experiments support an individual's voluntary trade-off between VWM number and precision. In 19 out of 20 experiments reported, when the exposure duration per stimulus item equalled or exceeded 100 ms/item, trade-off between the VWM number with precision occurred; however, when the exposure duration per stimulus item was equal or smaller than 50 ms/item, trade-off between the VWM number with precision did not occur. Therefore, it can be speculated that the different patterns of results in terms of trade-off between VWM number and precision could be determined by a critical value of the ratio of duration/set size (a value between 50–100 ms/item), and the two-phase VWM resource allocation model could explain such a threshold value influencing the trade-off.

TABLE 1 A summary of the studies on the voluntary trade-off between VWM number and precision. The lines highlighted in grey represent that participants were not able to voluntarily trade off the number and precision. * indicates the supplementary experiment.

Study	Exp	N	Setsize	Duration	Duration/set size	Voluntary trade-off?	In line with two-phase model?
Zhang and Luck (2011)	1a	13	4	200 ms	50 ms/item	No	Yes
	1b	13	4	200 ms	50 ms/item	No	Yes
	2	14	4	200 ms	50 ms/item	No	Yes
	3	10	4	200 ms	50 ms/item	No	Yes
	4	10	6	200 ms	33.3 ms/item	No	Yes
Gao et al. (2011)		19	2, 4	500 ms	125, 250 ms/item	Yes	Yes
Murray et al. (2012)	1	12	4	200 ms	50 ms/item	No	Yes
	2	20	4	200 ms	50 ms/item	No	Yes
	3	20	4	200 ms	50 ms/item	No	Yes
	4	20	4	200 ms	50 ms/item	No	Yes
Machizawa et al. (2012)	1	20	2	200 ms	100 ms/item	Yes	Yes
			4	200 ms	50 ms/item	No	Yes
	2	20	2	200 ms	100 ms/item	Yes	Yes
			4	200 ms	50 ms/item	No	Yes
Ye et al. (2014)		14	2, 3, 4	100 ms	25-50 ms/item	No	Yes
Fougnie et al. (2016)	1	18	5	1200 ms	240 ms/item	Yes	Yes
	*	18	5	200 ms	40 ms/item	No	No
	2	18	5	1200 ms	240 ms/item	Yes	Yes
Bocincova et al. (2017)		60	2, 4	150 ms	37.5, 75 ms/item	No	Yes
Ye et al. (2017)	1	47	4	200 ms	50 ms/item	No	Yes
	2	50	2	200 ms	100 ms/item	Yes	Yes
	3	47	4	500 ms	125 ms/item	Yes	Yes

8.3 Explanations for BFA in VWM

There are three possible explanations for why BFA could be observed in a VWM task. The first is that BFAs result from a faster rate of encoding rather than increased capacity. The second is that the probability of a target being forgotten is greater in the unilateral condition in the memory maintenance phase (Umemoto et al., 2010), and this results in better performance in the bilateral condition in the recall phase. The third is that BFA reflects enhanced memory ability in the maintenance phase when items are distributed across both hemifields. However, the probability of the first explanation is low. Umemoto et al. (2010) used sequentially presented stimuli and observed a bilateral advantage, suggesting that BFA could not be explained fully by differences in encoding quality. The probability of the second explanation is also hard to sustain because a previous study found that the number of items stored was not significantly reduced within a retention interval of one to four seconds (Zhang & Luck, 2009). The memory retention time in Umemoto et al. (2010) and in the present study was only 900 ms, so memory loss is unlikely to be the cause of BFA. The probabilities of the first and second explanations were excluded, so BFA in Study V mostly arose from enhanced memory ability in the maintenance phase.

The deeper reason for BFA in the maintenance phase should be discussed. There are two main theoretical explanations that could explain the precision advantage in the bilateral condition. Discrete resource theories (or slots-based theories) hold that the bilateral condition could have more slots to participate in memory processes compared to the unilateral condition. Alternatively, continuous resource theories hold that the bilateral condition has more memory resources. There are two points of difference between these two kinds of theories. First, whether the memory resources were discrete or continuous. Second, whether memory resources could be infinitely fractionized; that is, whether the number of memoranda is unbounded. In fact, the bilateral advantage in guess rate observed by Study V and Umemoto et al.'s (2010) study appears to be inconsistent with the continuous resource model. The resource model allows for VWM resources to be flexibly allocated between items in a display, with fewer resources per item and thus reduced precision as the set size increases. If BFA was driven by bilateral presentations having more memory resources than unilateral presentations, the representational precision should be different between the bilateral and unilateral conditions (rather than the probability of storage). One might argue that the lack of difference in precision was due to memory being excessively loaded, such that the limited resources allocated to each item were insufficient to cause differences in precision. However, in that case, the probability of storage should have been equal for the bilateral and unilateral conditions.

Therefore, the BFA can be explained according to the slots + averaging model: When the memory array's set size is greater than the number of slots, more available slots lead the guess rate (g) to decrease. When the set size of a memory array is less than the number of slots, more available slots lead the SD value to decrease. Therefore, both the bilateral precision advantage and the bilateral guess rate advantage can be attributed to having more slots involved in memory within the bilateral condition. In addition, when memory items were presented bilaterally, the SD at the 400-ms presentation time was significantly lower than at 200 ms, indicating that more slots were employed at 400 ms, which suggests that the slots are sequentially employed. However, there was no difference between 200 ms and 400 ms when memory items were presented unilaterally. This may be due to participants with low working memory capacity. Most of the participants could only remember two orientations in the unilateral condition (i.e., only two slots could be used in the unilateral condition). This suggests that no matter how long the memory array is presented, each item in the memory array only takes one slot. There may be other explanations for why the SD for the 400-ms presentation time was significantly lower than for 200 ms in Experiment 10. For example, because the observers were given abundant time to process the stimuli, more precise information could have been pulled into working memory, causing the SD to decrease. A study by Gao, Ding, Yang, Liang and Shui (2013) suggested that the processing of representations in VWM is from coarse-to-fine in the course of time. They assumed that coarse information enters VWM preceding detailed information. The results of Study V suggest that the decrease in SD cannot be explained by more precise information being pulled into working memory because of the single condition. If the representations created in VWM are based on a coarse-to-fine manner, then the SD for the single condition should be the same as the other two conditions. The present data show that the SD for the single condition was significantly smaller than for the other two conditions. In addition, Bays, Gorgoraptis et al. (2011) suggested that more resources can be used over time, but they did not contradict the idea that more memory slots can be used to improve precision over time.

Since the results of Study V might not be adequate enough to discern whether memory resources are discrete or continuous, a more reasonable explanation for more memory resources in the bilateral condition is high utilisation, which may stem from the allocation of more attentional resources. For example, the total amount of memory resources was the same in the two conditions, but the resource utilisation in VWM depends on how many attentional resources can be allocated. If there are more attentional resources in the bilateral condition, then this could make the bilateral condition have a higher utilisation. In fact, BFAs in visual attention tasks have been widely reported (Alvarez & Cavanagh, 2005; Delvenne & Holt, 2012). Therefore, this hypothesis is supported by the previous literature. It could also explain why previous BFA studies on working memory only found the effect on location and orientation rather than colour. The process of orientation is more likely tied to the involvement of visual attention. So, the BFA of orientation might be more likely to arise. In conclusion, this study shows for the first time that BFAs can be demonstrated using a precision index, and that the nature of BFAs is that more attentional resources are available when items are spread across the two hemifields.

8.4 Feature-based storing in VWM

In addition to investigating whether individuals can use dimension-based internal attention to control VWM resource allocation, Study VI also addressed another argument in the VWM literature. That is, what is the format of memory representations (Suchow, Fougnie, Brady, & Alvarez, 2014)? Both object-based storing and feature-based storing hypotheses have been proposed. The object-based storing hypothesis suggests that a given VWM representation is structured as a set of monolithic object representations, such that additional feature information will be maintained ‘for free’ after all features have been integrated into one memory unit (Luck & Vogel, 1997; Vogel et al., 2001). On the contrary, the feature-based storing hypothesis suggests that visual features, such as colours and orientations, are independent and stored separately from each other, such that objects have multiple feature levels of representation in VWM (Wheeler & Treisman, 2002). These hypotheses would predict different result patterns for the effect of a dimension-based retro-cue on a VWM task.

Based on the object-based storing hypothesis, because features are bound to an integrated object, participants cannot forget a task-irrelevant feature of an integrated object or weight resources to a task-relevant feature of an integrated object. As a result, an object-based storing hypothesis might expect that the dimension-based retro-cue would not result in a benefit. However, based on the feature-based storing hypothesis, because different features are stored separately, participants can use the dimension-based retro-cue to reduce memory load by forgetting task-irrelevant features or enhancing the memory of task-relevant features. As a result, according to a feature-based storing hypothesis, better performance is expected when a valid dimension-based retro-cue is presented to participants. In some sense, the predicted effect from this view is similar to that in a previous study, which presented two encoding displays and told participants which display was going to be tested and which could be dropped (Lepsien & Nobre, 2007). Therefore, the results of Study VI can weigh in on the debate between the object-based storing hypothesis and the feature-based storing hypothesis.

The results of Study VI support the feature-based storing hypothesis and reject the objected-based storing hypothesis. This is in line with Bays, Wu, et al.'s (2011) and Fougnie and Alvarez's (2011) studies. In their studies, participants were asked to remember five to six double dimension items. The results showed a strong independence of errors between feature dimensions, suggesting that participants could recall one feature accurately but forgot the other feature of the same object, thus supporting the feature-based storing hypothesis. However, there are still some challenges to the feature-based storing hypothesis from recent studies. Marshall and Bays (2013) found that task-irrelevant dimensions were encoded into VWM automatically when participants were asked to store a task-relevant dimension. This finding suggests the alternative conclusion that VWM encoding is an object-based rather than feature-based process. In Bays, Wu, et al.'s (2011) and Fougnie and Alvarez's (2011) studies, participants needed to remember five to six double dimension items; as VWM capacity was limited, participants could not encode and maintain all items with perfect fidelity in their studies. Marshall and Bays (2013) suggested that the conflicting prior results of Bays, Wu, et al.'s (2011) and Fougnie and Alvarez's (2011) studies may be due to involuntary failure or variability in the encoding process for each dimension, resulting in independent errors on recall. However, this explanation, suggested by Marshall and Bays (2013), does not account for the findings of Experiment 15. In Experiment 15, participants only needed to remember two items, which could be encoded and maintained perfectly, according to previous research (Luck & Vogel, 1997). As a result, there should be little to no failure or variability in encoding for each dimension in the present data. Yet, the results are consistent with VWM storage at the feature level. Therefore, Study VI provides new evidence to support the view that VWM representations can be stored in a feature-based manner.

8.5 Comparison of different VWM paradigms

Four paradigms were used in the present research: change detection task, change detection task with mask, recall task and recall task with retro-cue. I will give my opinions about these different paradigms based on my experience.

The change detection task is the most common paradigm for assessing VWM. As mentioned in the general introduction, this is due to the fact that behavioural results of the paradigm may be potentially contaminated by the decision-making process, and behavioural results are unable to distinguish the VWM quantity index from the VWM quality index. Thus, the change detection task was only used in Study II with ERP collection and in Study IV as a pre-task. However, its advantage is that by using Cowan's formula (Cowan, 2001), the VWM capacity for individuals can be estimated. The VWM capacity measurement takes little time (about 10 minutes), and this method was used in Study IV. Therefore, the change detection task is a cost-effective paradigm for the study of individual differences in VWM capacity.

The paradigm of change detection task with mask was used in Study I. In order to precisely control the memory consolidation time of an individual, a mask was added to the change detection task in the blank between the memory array and the test array. The results show the differences in the processing mechanism of individuals at different lengths of memory consolidation. This task can be considered as a basic paradigm for investigating VWM consolidation.

In Study I and Study II, ERP data were collected during the VWM tasks (change detection task, and change detection task with mask). The CDA component was used to measure the number of items stored in VWM. Interestingly, the ERP results were inconsistent with the behavioural results. This suggests that the results of the CDA component are more reliable than the behavioural results in reflecting VWM processing. Therefore, when it is necessary to investigate the pure VWM mechanism, the ERP technique is a more ideal choice than the behavioural measurement of VWM. However, one problem of the ERP technique is that participants need to complete many trials (2–10 times compared to the change detection task) to ensure data quality. Therefore, in the experiments using the CDA component, the experimental designs cannot be too complicated, and the number of conditions is fairly limited (e.g., about 50 minutes for three conditions).

The recall task was the main paradigm used in this research because it was focused on the issue of VWM resource allocation, which was needed to observe VWM quantity and quality at the same time. By using different data-fitting models, the quantity index and the quality index could be separated. Although there are still potential problems that cannot be avoided in behavioural recall tasks, the recall task is better than the ERP experiment in obtaining an effective VWM quality index. Therefore, this task can be considered as a basic paradigm for measuring VWM precision.

The paradigm of the recall task with retro-cue was used in Study VI. In order to investigate the impact of internal attention on representations during VWM maintenance, a retro-cue was added to the recall task in the blank between the memory array and the recall array. More importantly, a dimension-based retro-cue was invented in Study VI. Although studies on object-based retro-cues have been in the literature for more than 10 years, the dimension-based retro-cue has only been proposed recently. The paradigm of the recall task with dimension-based retro-cue could contribute a new perspective to studies of internal attentional impact on VWM. Future studies can use this paradigm to further explore the mechanism of resource allocation during VWM maintenance.

9 CONCLUSION AND FUTURE DIRECTION

This research was divided into four parts. The first part was Study I, which provided convergent evidence for the behavioural studies and helped resolve previous controversies. The results suggest that the manner and bandwidth of VWM consolidation are determined by the stimulus feature. Consolidation for colour material involves parallel processing with a bandwidth of two items; but for orientation materials, participants use serial processing.

The second part was Study II–IV, which determined the existence of a two-phase VWM resource allocation mechanism in VWM consolidation, which cannot be allocated voluntarily at short consolidation times but can instead be allocated voluntarily at long consolidation time. In addition, an individual's VWM capacity affects his or her ability to allocate resources voluntarily. The higher the VWM capacity, the stronger the trade-off ability.

The third part was Study V, which found that the presenting location of memory stimuli in the VWM consolidation phase affects the allocation of VWM resources. Bilateral presentation is a benefit for the memory rate in a short consolidation time and a benefit for memory precision in a long consolidation time. These benefits come from the presentation of memory targets in bilateral visual hemifields rather than from other distribution factors

The last part was Study VI, which found that individuals can use dimension-based internal attention to reallocate resources voluntarily during the VWM maintenance phase. These results rejected the possibility that the benefit was only caused by protection from degradation, or by reducing interference from the processing of a non-reported dimension during the response phase. The results further support the notion that visual features could be independent and stored separately from each other, such that objects have multiple feature levels of representation in VWM.

Based on the present research, the new findings of VWM consolidation and maintenance mechanism are fruitful for further work. However, this research has posed many questions in need of further investigation. Some future research directions are as follows:

1) The bandwidth of additional different materials (e.g., motion direction,

complex shapes) needs to be examined. The bandwidth mechanism of VWM consolidation needs to be confirmed by the fMRI technique to determine the brain mechanisms for VWM consolidation in different materials.

2) The interaction mechanism between the first phase and the second phase of the two-phase model needs to be explored – for example, how an individual enters the second phase from the first phase. It is necessary to use the fMRI technique to explore the brain mechanism of the two-phase model.
3) Due to the restriction of the CDA component, it is often necessary to ask participants to memorise the items from one visual hemifield. On the contrary, behavioural studies of facial VWM have typically presented memory items bilaterally. It is necessary to explore the BFA effect by using the other ERP component related to VWM processing.
4) It is necessary to test whether the object-based retro-cue benefit and the dimension-based retro-cue benefit are derived from the same mechanism.

YHTEENVETO (FINNISH SUMMARY)

Yhteenvetona todettakoon, että visuaalisen työmuistin aavulla ihmisen kognitiivinen järjestelmä ylläpitää visuaalista informaatiota, joka on tarpeellista käynnissä olevan tehtävän näkökulmasta. Tämän tallennustilan avulla voimme ylläpitää visuaalista informaatiota ulkopuolisesta ympäristöstä, mikä auttaa meitä yhdistämään visuaalisen informaation jatkuvaksi visuaaliseksi kokemukseksi. Tutkimuksessa tarkasteltiin visuaalisen työmuistiresurssin jakamismekanismia informaation konsolidaatio- ja ylläpitovaiheissa.

Ensimmäisessä tutkimuksessa selvitettiin, onko konsolidaatiomenetelmä riippuvainen visuaalisen informaation laadusta. Tulokset osoittivat, että ärsykkeen piirteet määrittelevät visuaalisen työmuistin konsolidaation tavan ja kaistanleveyden. Toisessa tutkimuksessa tarkasteltiin visuaalisen työmuistin kapasiteetin suhdetta työmuistin tarkkuuteen väriominaisuuksien yhteydessä. Tulokset eivät osoittaneet kompromisseja raportoitavien kohteiden määrän ja laadun välillä. Kolmannessa tutkimuksessa testattiin muistettavan ärsykesarjan koon ja altistuksen keston vaikutusta. Tulokset viittaavat siihen, että ihminen voi ohjata tahdonalaisesti kompromisseja raportoitavien kohteiden lukumäärän ja tarkkuuden välillä vain pitkän altistuksen tai pienen muistisarjan koon yhteydessä, mutta ei lyhyen altistuksen ja suuren sarjakoon yhteydessä. Neljännessä tutkimuksessa selvitettiin yksilöllisen visuaalisen työmuistin kapasiteetin vaikutusta kompromissikykyyn raportoitavien kohteiden lukumäärän ja tarkkuuden välillä. Tulokset osoittivat, että koehenkilöt, joilla on pieni visuaalisen työmuistin kapasiteetti, ja jotka osoittivat heikompaa kykyä kompromisseihin, työmuistiresurssien allokointi on suurelta osin ärsykkeiden ohjaamaa (ei tahdonalaista), kun taas koehenkilöt, joilla on korkea visuaalisen työmuistin kapasiteetti, kykenevät allokoimaan ylimääräisiä resursseja kompromissien tekemiseen raportoitavien kohteiden lukumäärän ja tarkkuuden välillä. Viidennessä tutkimuksessa tutkittiin näkökentän molemmilla puoliskoilla esitetyn ärsykkeen tuomaa etua (bilateral field advantage) visuaalisen työmuistiresurssin kohdentamisessa. Tulokset osoittivat, että ilmiö voi parantaa sekä visuaalisen työmuistin nopeutta että tarkkuutta. Kuudennessa tutkimuksessa tutkittiin ulottuvuus-pohjaisen tahdonalaisen tarkkaavuuden vaikutusta visuaaliseen työmuistiin. Tulokset osoittivat, että koehenkilöt pystyivät hyödyntämään ulottuvuus-pohjaista tahdonalaista tarkkaavuutta työmuistiresurssin kohdentamiseen ärsykkeiden tiettyyn dimensioon (kuten väri).

Tutkimus voidaan jakaa neljään osaan. Ensimmäinen osa (tutkimus I) selvitti resurssien kohdentamista visuaalisen työmuistin konsolidaatiossa erilaisten materiaalien kohdalla, jolloin havaittiin, että visuaaliset työmuistiresurssit kohdennettiin sarjallisesti orientointimateriaaleihin, mutta värimateriaalien kohdalla rinnakkain. Toisessa osassa (tutkimukset II-IV) tutkittiin tahdonalaista resurssien kohdentamista konsolidaatioprosessin aikana ja ehdotettiin kaksivaiheista mallia resurssien kohdentamisen selittämiseksi. Lisäksi tulokset osoittivat yksilöllisen visuaalisen työmuistin kapasiteetin vaikutukset tähän kaksivaiheiseen prosessiin. Kolmannessa osassa (tutkimus V) tutkittiin muistettavien visuaalisten kohteiden sijaintien vaikutusta visuaalisen työmuistiresurssin allokointiin ja havaittiin, että tarkkaavuusresursseja on käytettävissä enemmän, kun kohteet levitetään molempiin näkökentän puoliskoihin. Neljäs osa (tutkimus VI) selvitti resurssien kohdentamista informaation ylläpitovaiheessa, jolloin havaittiin, että koehenkilöt kykenivät jakamaan resursseja tahdonalaisesti ulottuvuusperusteisesti. Yhteenvetona, esitelty tutkimus hyödynsi ERP-mittausta (event-related potentials) ratkaistakseen kiistan visuaalisen työmuistin konsolidointitavoista, esitteli kaksivaiheisen mallin selittääkseen tahdonalaista visuaalisen työmuistiresurssin ohjausta koskevat aikaisemmat ristiriitaiset tulokset, selvitti molemmilla näkökentän puoliskoilla esitettävän ärsykkeen tuomaa etua visuaalisen työmuistiresurssin kohdentamisessa ja esitteli uuden paradigman tutkia ulottuvuus-pohjaista sisäistä tarkkaavuutta. Tutkimus tarjoaa uusia todisteita ja tapoja tutkia resurssien kohdentamisesta visuaalisen työmuistin konsolidointi- ja ylläpitovaiheissa.

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ORIGINAL PAPERS

I

THE BANDWIDTH OF VWM CONSOLIDATION VARIES WITH THE STIMULUS FEATURE: EVIDENCE FROM EVENT-RELATED POTENTIALS

by

Renning Hao, Mark W. Becker, Chaoxiong Ye, Qiang Liu & Taosheng Liu, 2017

Journal of Experimental Psychology: Human, Perception, and performance.
Advance online publication.
Available online: http://dx.doi.org/10.1037/xhp0000488

The bandwidth of VWM consolidation varies with the stimulus feature： evidence from event-related potentials

Renning Hao[a], Mark W. Becker[b], Chaoxiong Ye[a,c], Qiang Liu[a], Taosheng Liu[b]

a. Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian, China, 116029

b. Department of Psychology, Michigan State University, East Lansing, MI 48824

c. Faculty of Information Technology, University of Jyväskylä, Jyväskylä, Finland, 40014

Running Head: Bandwidth of VWM consolidation

Number of manuscript pages: 18

Number of tables: 0

Number of figures: 7

Correspondence to:

Qiang Liu,
Research Center of Brain and Cognitive Neuroscience,
Liaoning Normal University,
Dalian 116029, China
E-mail: lq780614@163.com
Or
Taosheng Liu,
Department of Psychology,
Michigan State University,
East Lansing, MI 48824,
E-mail: tsliu@msu.edu

Acknowledgements:

This research was supported by grants from the National Natural Science Foundation of China (NSFC31571123) to Q. L., and from the National Institutes of Health (NIH R01EY022727) to T. L.

Abstract

Our previous work suggests that two colors can be consolidated into visual short-term memory (VSTM) in parallel without a loss of memory precision, while consolidation of two orientations is performed in a strictly serial manner. Those experiments compared VSTM performance for simultaneously and sequentially presented stimuli. However, there is still controversy about whether the bandwidth for consolidation is determined by the type of information. To further investigate this issue, here we measured electroencephalography while participants attempted to consolidate one, two or four simultaneously presented colors (Experiment 1) or orientations (Experiment 2) under limited presentation times. We used the contralateral delay activity (CDA) as an electrophysiological marker of the number of items that were consolidated. For colored stimuli, the CDA amplitude increased between set-size one and two but did not further increase for set size four. By contrast, for orientation, the CDA amplitude remained at the set size one amplitude as set size increased to two or four items. Furthermore, in a long exposure duration (300 ms) condition that did not limit the consolidation process, the CDA amplitude pattern indicated that VSTM capacity is limited to about three colored items and about two orientation items in our paradigm. Thus, the CDA effects observed in the short presentation time was not limited by VSTM storage, but rather by consolidation. These results are consistent with our previous behavioral research and suggest that the bandwidth of VSTM consolidation is determined by the stimulus feature.

Keywords: visual short-term memory, bandwidth, consolidation, contralateral delay activity

The public significance of the study

Previous studies on the bandwidth of visual short-term memory consolidation relied on behavioral measures, which were affected by assumptions about the underlying processes, and as a result have produced inconsistent conclusions. We used the contralateral delay activity, an electrophysiological measure to probe the bandwidth of consolidation for the first time. Our results show distinct patterns for consolidating color and orientation information, thus providing converging evidence for the behavioral studies and help resolve previous controversies.

Introduction

Early representation of visual information is fleeting, unprocessed, and subject to masking (Sperling, 1960). In order to further process visual stimuli, one must consolidate the volatile perceptual representation into a relatively stable and durable VSTM representation (Jolicoeur & Dell'Acqua, 1998; Vogel, Woodman, & Luck, 2006). It is generally accepted that visual short-term memory (VSTM) has a capacity of about 3~4 items (Luck & Vogel, 1997; Pashler, 1988). However, in recent years, researchers have begun to focus on the characteristics of this consolidation process, and have found that the capacity of this VSTM consolidation process is also limited (Jolicoeur & Dell'Acqua, 1998; Stevanovski & Jolicoeur, 2007, 2011; Vogel, Woodman, & Luck, 2006; West, Pun, Pratt, & Ferber, 2010; Zhang & Luck, 2008). For example, in a masked change detection task, Vogel et al. (2006) found performance initially improved as the interval between a memory array and masks increased, but then reached a plateau such that additional time did not further improve memory performance. However, such findings cannot reveal whether the limits of consolidation result from a serial process, which allows consolidation of only one item at a time, or from a limited-capacity parallel process, which allows consolidation of multiple items but with limited capacity.

Huang and colleagues suggested that items are consolidated into VSTM serially, as their Boolean map theory predicts that only one feature value per perceptual dimension can be consolidated at a time (Huang, 2010; Huang, 2015; Huang & Pashler, 2007; Huang, Treisman & Pashler, 2007). In their experiment, a change detection task was used with two simple color squares presented sequentially or simultaneously. Results showed that performance was better in the sequential than simultaneous condition, suggesting that it is difficult to consolidate two colors simultaneously (Huang et al., 2007). However, Mance, Becker and Liu (2012) pointed out that there were contingencies in Huang at al.'s study that may have allowed participants to predict the location and colors of items in the sequential condition, potentially leading to superior performance in the sequential condition that was unrelated to consolidation limits. Mance et al. (2012) also presented two color squares either sequentially or simultaneously in a change detection task. Importantly, they removed the contingencies and presented the stimuli for an exposure duration estimated to be just long enough to consolidate a single item. They found no difference in performance between the sequential and simultaneous condition, although a sequential advantage was observed when set size was increased to three or four. These results suggested that the parallel consolidation of colors is possible but the capacity of this parallel consolidation process was limited to two items. In a follow-up study, Miller, Becker & Liu (2014) used a color recall task in conjunction with model fitting to characterize the memory precision and guess rate. The results found no change in memory precision or guess rate between simultaneous and sequential presentation of two colors, suggesting that two colors could be consolidated in parallel without cost.

In another set of studies, the consolidation of orientation information was investigated by presenting two oriented gratings either sequentially or simultaneously. For these orientation stimuli, memory performance was better for sequential than simultaneous presentation, suggesting a severe capacity limit in consolidating orientation information (Becker, Miller & Liu, 2013). To further study the nature of the consolidation limit, Liu & Becker (2013) used a recall task in conjunction with model fitting and found that simultaneous presentation resulted an increase in guess rate with no change in memory precision, suggesting that the consolidation of orientation was a strictly serial process (Liu & Becker, 2013). They proposed that the capacity limit, or bandwidth, of VSTM consolidation depends on the stimulus feature. Orientation might require more processing resource than color, and thus while two colors can be consolidated in parallel, two orientations are consolidated in a strictly serial manner.

However, Rideaux et al. (2015, 2016) have challenged the conclusion regarding orientation, arguing that two orientations can also be consolidated via a limited-capacity parallel mechanism. Their main support for this claim (Rideuax, et al., 2016) is their finding that simultaneous presentation of two orientations produced higher guess rates and decreased precision compared to sequential presentation. However, it is worth noting that this was true only when the location of items was predictable in the sequential condition, which may have allowed covert shifts of attention prior to stimulus presentation that artificially increased memory precision in the sequential condition. When the location of items was unpredictable (their Experiment 2), their results were consistent with Becker, Miller & Liu (2013)'s: the simultaneous presentation of two orientations produced higher guess rates but equivalent memory precision as sequential presentation. While Liu & Becker (2013) have argued that this pattern is strong evidence for a strictly serial mechanism, they suggested that their data are evidence for a parallel consolidation mechanism. Their rationale was that the guess rate for sequential presentation was not 50%. While under an ideal condition a strictly serial mechanism should yield a 50% guess rate, we believe that there are a number of reasons why this precise 50% prediction might not hold. For instance, if the consolidation rate for the first item is very rapid in some trials, in those trials there may be adequate time to serially process the second item, thereby reducing the guess rate. In addition, it is possible that certain pairs of two simultaneously presented orientations support a strategy that allows for both orientations to be consolidated as a single stimulus; for instance, if the two orientation were about 90° apart, participants might encode a single angle of 90°, i.e., they could remember the two orientations as a single spatial configuration.

In short, while we believe the simultaneous vs. sequential paradigm is a powerful method for investigating consolidation into VSTM, the interpretation of results depends on the set of assumptions one makes about the task. Thus, it seems that a converging method, and particularly one that does not require comparisons across conditions with different numbers of stimuli per display, would help clarify that results are due to consolidation mechanisms rather than other strategic or low-level perceptual differences that may differ across simultaneous and sequential presentation conditions.

In the present experiments, we used an electrophysiological marker, contralateral delay activity (CDA), to probe VSTM consolidation processes. Importantly, this method does not require comparing a simultaneous to a sequential condition, thereby eliminating the interpretational issues raise above. The CDA is characterized by a negative slow wave that is larger over the contralateral than ipsilateral hemisphere to the memorized visual field (Fukuda & Vogel, 2009; Ikkai, McCollough & Vogel, 2010; Luck & Vogel, 2013; Vogel & Machizawa, 2004; Vogel, McCollough & Machizawa, 2005; Woodman & Vogel, 2008). The amplitude of the CDA scales with the number of items held in memory (Drew & Vogel, 2008; Jost, Bryck, Vogel & Mayr, 2011; Luria & Vogel, 2011, 2014; McCollough, Machizawa & Vogel, 2007; Vogel & Machizawa, 2004; Vogel, McCollough & Machizawa, 2005; Woodman & Vogel, 2008) but not with the resolution or complexity of the items (Balaban & Luria, 2015; Ye, et al.,2014). Given that the CDA scales with the number of items held in VSTM, in the present study, we used the CDA to examine whether multiple colors (Experiment 1) or orientations (Experiment 2) can be consolidate in parallel or are consolidated in a serial manner.

We asked participants to remember one, two or four simultaneously presented items while severely limiting the consolidation time to the duration needed to consolidate a single item. We hypothesize that if the consolidation is a serial process, only a single item should be consolidated regardless of the set size of the display. Thus, there would be no difference among the CDA amplitudes for the different set sizes (Fig. 1a). However, if the items could be consolidated into VSTM in parallel, the CDA amplitude should increase with set size until the bandwidth of consolidation is exhausted (Fig. 1b). Furthermore, we also ran a condition in which consolidation time was not severely limited (300 ms exposure duration). This long exposure duration is used to measure the capacity of VSTM storage to ensure that any limits we find in the minimum time condition can be attributed to limits in the consolidation process rather than limits in storage capacity. In this condition, we would expect CDA amplitude to increase with set size until the total capacity is reached (Fig. 1c).

INSERT FIGURE 1 ABOUT HERE

Experiment 1

Methods

Participants

Twenty students (11 females) from Liaoning Normal University volunteered to participate in this experiment for paid compensation. They reported no history of neurological problems, reported having normal color vision and normal or corrected-to-normal visual acuity. Signed informed consent was provided by each participant prior to participation, and all procedures were in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

We based our sample size on a previous study that compared CDA produced by storing one item verses two items (Experiment 2 of Luria & Vogel, 2011). Based on the method proposed by Thalheimer and Cook (2002) for estimating effect sizes from F statistics, we estimated that their effect size was 1.39 for that comparison. To determine our sample size we assumed that our effect size would only be 50% of their effect size (.7), and calculated the sample size required to yield a power of .85 given $\alpha = .05$ for a paired-sample t-test (Faul, Erdfelder, Lang, & Buchner, 2007). This calculation yielded a sample size of 21.

Stimuli

In Experiment 1, the stimuli were presented with E-prime software on a 21-inch cathode ray tube (CRT) monitor (800 * 600 pixel, 144-Hz refresh rate). Participants were seated in an electrically shielded and sound-attenuated recording chamber at a viewing distance of 60 cm. Each memory item was a colored square with the color randomly chosen without replacement from a set of six highly discriminable colors (RGB values, red: 233,0,0; green: 30,138,18; blue: 26,49,178; orange: 210,85,7; yellow: 231,228,66; purple: 156,0,158). The mask consisted of a 6 × 6 multicolored checkerboard pattern composed of the same six colors as the stimuli; the color of each square in the mask was randomly assigned for each mask presentation. Each colored square and mask subtended 0.65 ° × 0.65 ° of visual angle.

Procedure: Main task

Participants performed a color identification task with the trial structures depicted in Fig. 2. Items were presented within 4 ° × 7.3 ° rectangular regions bilaterally, centered 3 ° to the left and right of the middle of the screen. The memory array consisted of 1, 2 or 4 different colored squares which were selected at random in each hemifield with the constraint that the given color could appear no more than once in each hemifield. Stimulus positions were randomized on each trial, with the constraint that the distance between squares within a hemifield was at least 2 ° (center to center).

Each trial started with the presentation of a fixation point (“+”) in the middle of the screen. Then, two arrow-cues were presented for 200 ms above and below fixation, indicating the to-be-attended side on that trial. After a variable delay which ranged from 100 to 200 ms, the memory array was presented for 300 ms or the minimum time (the duration was determined by a threshold procedure described below). A mask was then presented for 100 ms, which was followed by a retention interval (when only the fixation cross was presented) of 900 ms and then the test array. The test array remained visible for 2500 ms or until a response was made. A 1000 ms period preceded the start of the next trial. Participants were required to keep their eyes fixated at the central cross while storing the colors in the hemifield indicated by the cue. The probe array in the cued hemifield was different from the corresponding color in the memory array in 50% of trials; they were identical in the remaining trials. When a colored square changed, a new colored square that was not used in the memory array would be randomly selected from the remaining colors. The task was to indicate whether the test array was identical to the memory array, with accuracy rather than response speed being stressed.

We varied set size at 3 levels (1, 2 and 4) at two exposure durations: 300 ms vs. minimum time, with all six conditions intermixed within blocks. All participants completed at least 12 trials of practice to ensure the participants understood the instructions and a total of ten blocks of 72 trials each, resulting in 120 trials per condition.

INSERT FIGURE 2 ABOUT HERE

Procedure: Thresholding exposure duration

For each participant, we determined the minimum exposure duration required to consolidate a single colored item that was presented alone in its hemifield. Prior to the main task, each participant ran four blocks (64 trials each) of this thresholding task. The method of constant stimuli was used with eight durations: 7 ms, 14 ms, 28 ms, 56 ms, 98 ms, 154 ms, 224 ms and 308 ms. In these blocks, a single color stimulus was presented and masked in a random location within each hemifield (within 4 * 7.3° rectangular regions bilaterally, centered 3° to the left and right of the middle of the screen) (see Fig. 3). Participants indicated whether the test item was identical to the memory item. Proportion correct was calculated for each exposure duration and fitted with a Weibull function using psignifit (Wichmann & Hill, 2001). Stimulus duration that yielded an overall accuracy of 80% correct was used in the main task.

INSERT FIGURE 3 ABOUT HERE

Electroencephalography recording and analyses

Electroencephalographic (EEG) data was recorded with a QuickAmp amplifier (Brain Products GmbH, Munich, Germany). EEG was recorded from 64 tin electrodes mounted in an elastic cap, using the International 10/20 system. Vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG) were recorded with two electrodes, one placed below the left eye, and another placed next to the right eye. Impedance at each electrode site was maintained below 5 kΩ. The EEG and EOG were amplified using a 100 Hz low-pass and digitized at a sampling rate of 500 Hz. The EEG was algebraically re-referenced offline to the average of the left and right mastoids during post-recording analyses and segmented into 1000 ms epochs starting from 100 ms before the memory array onset. Trials with remaining artifacts exceeding ±75μV in amplitude were rejected. Participants with trial rejection rates that exceeded 25% were excluded from the analyses. No subject was excluded on this basis.

Two pairs of electrode sites at posterior parietal (P7/P8 and PO7/PO8) were chosen for analysis. The contralateral waveforms were computed by averaging the activity recorded at left hemisphere electrode sites when participants were cued to remember the memory array in the right hemifield, and vice versa. The CDA was usually measured by subtracting the ipsilateral activity from the contralateral activity, with a measurement window around 400-1000 ms after the onset of the memory array (Luria & Vogel, 2011; Peterson et al., 2015). In the present study, however, the memory array was followed by a mask array, which is necessary to limit the time for consolidation, but raised the potential problem that responses to the mask may overlap with the early phase of the CDA. For example, the masks could evoke a Pd component associated with termination of attention (Sawaki et al., 2012). Given that the CDA is postulated to reflect sustained neural activity throughout the entire delay period, we averaged the CDA in a time window of 600-1000 ms after memory array onset- a window that should be late enough to minimize the effect of the mask on the CDA. The average CDA waveforms were smoothed by applying a 10 Hz low-pass filter.

Results and Discussion

Behavioral results

The average minimum time across participants was 60 ms (range = 21-147 ms, SD = 32 ms). Percent correct (accuracy) for the minimum time conditions and 300 ms conditions were calculated for each participant. An ANOVA including the set size (1 vs 2 vs 4) and exposure duration (300 ms vs. minimum time) on accuracy yielded main effects of set size ($F_{2,38} = 283.99$, $p < .001$, $\eta_p{}^2 = .94$) and exposure duration ($F_{1,19} = 93.89$, $p < .001$, $\eta_p{}^2 = .83$). The interaction between the two factors was also significant. ($F_{2,38} = 5.71$, $p < .01$, $\eta_p{}^2 = .23$) (Fig. 4a). Post hoc analysis revealed that there were both significant difference in accuracy between 1 and 2 colors (1 color: M = .83, SD = .08; 2 colors: M = .73, SD = .09; $t_{19} = 8.01$, $p < .001$, Cohen's *d* = 1.15), and between 2 and 4 colors (2 colors: M = .73, SD = .09; 4 colors: M = .59, SD = .05; $t_{19} = 8.86$, $p < .001$, Cohen's *d* = 2.02) in minimum time condition. Similarly, those differences were also significant in the 300 ms condition (1 color: M = .95, SD = .02; 2 colors: M = .90, SD = .06; 4 colors: M = .69, SD = .07; 1 vs. 2 colors: $t_{19} = 4.20$, p

< .001, Cohen's *d* = 1.11; 2 vs. 4 colors: $t_{19} = 14.88$, $p < .001$, Cohen's *d* = 3.24). Such steady decline in behavioral accuracy at larger set sizes is expected as decision noise or interference also increases with set size (Eckstein et al., 2000; Palmer et al., 2000). Thus, behavioral accuracy in the change detection task is not diagnostic of whether the consolidation process is parallel or serial. Indeed, such considerations prompted previous work to compare sequential and simultaneous presentation conditions at the same set size (e.g., Huang & Pashler, 2007; Mance, Becker & Liu, 2012).

INSERT FIGURE 4 ABOUT HERE

Electrophysiological results

By leveraging the properties of the CDA, we were able to directly assess how many items were consolidated simultaneously without the need to compare to a sequential condition. The grand average subtraction waveforms of CDA in the minimum time condition and 300 ms condition for each set size are shown in Fig.4b and 4c, respectively. The CDA emerged after 400 ms and persisted throughout the retention period. We used a 600-1000 ms window (shaded area) to calculate CDA amplitude, due to potential mask-evoked ERPs (see Methods). The averaged CDA amplitudes are shown in Fig 4d. An ANOVA including set size (1 vs 2 vs 4) and exposure duration (minimum time vs. 300 ms) on mean amplitude yielded main effect of set size ($F_{2,38} = 17.05$, $p < .001$, $\eta_p^2 = .47$), but no effect for duration conditions ($F_{1,19} = .66$, $p > .05$). The interaction between the two factors was significant ($F_{2,38} = 5.12$, $p < .05$, $\eta_p^2 = .21$).

For the minimum time condition, planned comparisons revealed that there was a significant difference in amplitude between 1 and 2 colors (1 color: M = -.88, SD = .94; 2 colors: M = -1.27, SD = 1.15; $t_{19} = 2.61$, $p < .05$, Cohen's *d* = .37), but no significant difference between 2 and 4 colors (2 colors: M = -1.27, SD = 1.15; 4 colors: M = -1.42, SD = 1.38; $t_{19} = 1.11$, $p > .05$). The finding that the CDA amplitude increased from set-size one to set-size two, suggests that two items can be consolidated into VSTM in parallel. However, the fact that there was no further increase in CDA between set-size two and four, suggests that there is a limit in the number of items that can be processed in parallel. These results are consistent with our prediction (see Fig. 1b) and suggest that the consolidation bandwidth is at least 2 items. These results are also consistent with previous behavioral studies (Mance, Becker & Liu, 2012; Miller, Becker & Liu, 2014), which suggested that consolidating color information proceeds in a parallel manner with the bandwidth limited to two items.

For the 300 ms condition, planned comparisons revealed that there were both significant difference in amplitude between 1 and 2 colors (1 color: M = -.55, SD = .91; 2 colors: M = -1.05, SD = 1.01; $t_{19} = 3.02$, $p < .01$, Cohen's *d* = .52), and between 2 and 4 colors (2 colors: M = -1.05, SD = 1.01; 4 colors: M = -1.74, SD = 1.12; $t_{19} = 3.26$, $p < .01$, Cohen's *d* = .64). The fact that the CDA amplitude increased between 2 and 4 colors when we prolonged the stimulus duration to 300 ms, thereby removing the constraint on consolidation, suggests that at least three colors can be stored within VSTM. This pattern is consistent with our prediction regarding CDA amplitude when consolidation time is relaxed (see Fig. 1c)

In sum, our minimum time results support the notion of parallel consolidation of two simultaneously presented colors, but the bandwidth of consolidation prohibits more than two items from being consolidated. The 300 ms condition provides evidence that this limit is due to consolidation rather than storage capacity limitations. In Experiment 2, we extend this method to the consolidation of oriented gratings in order to investigate whether the process of consolidating orientation information also occurs in parallel or occurs serially.

Experiment 2

Methods

Participants

Twenty-two students (12 females) from Liaoning Normal University volunteered to participate in this experiment for paid compensation. They reported no history of neurological problems, reported having normal orientation vision and normal or corrected-to-normal visual acuity. Signed informed consent was provided by each participant prior to participation, and all procedures were in compliance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Stimuli

The main apparatus was similar to that used in Experiment 1 except visual stimuli were sinusoidal gratings (contrast: 0.7, spatial frequency: 3 cycle/deg) in a circular aperture presented on a gray background. The edge of the aperture was smoothed such that no sharp change in luminance was present between the grating and the background. The mask stimulus was a circular aperture containing pixel noise, with random luminance levels in a uniform distribution. Each orientation stimuli subtended 0.9 ° × 0.9 °of visual angle and mask subtended 1 ° × 1 °of visual angle.

Procedure: Main task

The procedure and main task were similar to that used in Experiment 1 with the trial structures depicted in Fig. 5. The memory array consisted of 1, 2 or 4 different gratings which could be in one of 12 orientations :10 °, 24 °, 38 °, 52 °, 66 °, 80 °, 100 °, 114°, 128°, 142°, 156° and 170°. Stimulus positions were randomized on each trial, with the constraint that no two gratings within the same hemifield had the same orientation and that the distance between gratings within a hemifield was at least 2° (center to center). When a grating changed its orientation in the probe array, a new orientation with a 90° difference would be selected.

Similar to Experiment 1, we varied set size at 3 levels (1, 2 and 4) at two exposure durations: 300 ms vs. minimum time, with all six conditions intermixed within blocks. All participants completed at least 12 trials of practice to ensure the participants understood the instructions and a total of ten blocks of 72 trials each, resulting in 120 trials per condition.

INSERT FIGURE 5 ABOUT HERE

Procedure: Thresholding exposure duration

The procedure of thresholding exposure duration was the same as that used in previous experiment except the stimuli were gratings (see Fig. 6).

INSERT FIGURE 6 ABOUT HERE

Electroencephalography recording and analyses

The EEG recording and analysis procedures were identical to those used in Experiment 1. The time range for measuring the CDA was also 600–1000 ms after memory array onset, to avoid contamination of mask-evoked ERPs. Participants with trial rejection rates that exceeded 25% were excluded from the analyses; this led to the exclusion of two participants.

Results and Discussion

Behavioral results

The average minimum time across participants was 57 ms (range = 7-119 ms, SD = 33 ms). An ANOVA including set size (1 vs 2 vs 4) and exposure duration (300 ms vs. minimum time) on accuracy yielded main effects of set size ($F_{2,38} = 385.62$, $p < .001$, $\eta_p{}^2 = .95$) and exposure duration ($F_{1,19} = 111.06$, $p < .001$, $\eta_p{}^2 = .85$). The interaction between the two factors was also significant ($F_{2,38} = 18.61$, $p < .001$, $\eta_p{}^2 = .49$) (Fig. 7a). Post hoc analysis revealed that there were both significant difference between 1 and 2 orientations (1 orientation: M = .84, SD = .08; 2 orientations: M = .69, SD = .08; $t_{19} = 11.92$, $p < .001$, Cohen's *d* = 1.88), and between 2 and 4 orientations (2 orientations: M = .69, SD = .08; 4 orientations: M = .56, SD = .04; $t_{19} = 7.93$, $p < .001$, Cohen's *d* = 2.01) in minimum time condition. Similarly, those differences were also significant in the 300 ms condition (1 orientation: M = .95, SD = .03; 2 orientations: M = .85, SD = .09; 4 orientations: M = .62, SD = .05; 1 vs. 2 orientations: $t_{19} = 6.13$, $p < .001$, Cohen's *d* = 1.50; 2 vs. 4 orientations: $t_{19} = 17.86$, $p < .001$, Cohen's *d* = 3.32). Similar to Experiment 1, behavioral accuracy also showed a steady decline as set size increased. Again, such decline is expected given associated increase in decision noise or interference when the set size increased and thus cannot reveal the nature of the performance limit.

INSERT FIGURE 7 ABOUT HERE

Electrophysiological results

The CDA emerged at 400 ms and persisted throughout the retention period. The grand average subtraction waveforms of CDA in the minimum time and 300 ms conditions for each set size are shown in Fig. 7b and 7c, respectively. An ANOVA including set size (1 vs 2 vs 4) and exposure duration (minimum time vs. 300 ms) on mean amplitude yielded main effect of set size ($F_{2,38} = 5.18$, $p = .01$, $\eta_p^2 = .21$), but no effect for exposure duration ($F_{1,19} = .057$, $p > .05$). The interaction between the two factors was also significant ($F_{2,38} = 5.08$, $p < .05$, $\eta_p^2 = .21$) (Fig. 7d).

For the minimum time condition, planned comparisons revealed that there were no significant difference in amplitude between 1 and 2 orientations (1 orientation: M = -.75, SD = .89; 2 orientations: M = -.70, SD = .82; $t_{19} = -.37$, $p > .05$) and between 2 and 4 orientations (2 orientations: M = -.70, SD = .82; 4 orientations: M = -.87, SD = .73; $t_{19} = 1.16$, $p > .05$). The fact that the CDA magnitude is constant across the three set size conditions, suggests that only one orientation was consolidated into VSTM in the minimum consolidation time regardless of the set size. This pattern is precisely the prediction of a strictly serial process (see Fig. 1a) and is consistent with previous behavioral studies (Becker, Miller, & Liu, 2013; Liu, & Becker, 2013; Miller, Becker, & Liu, 2014) suggesting serial consolidation of orientation information.

For the 300 ms condition, there was a significant difference in amplitude between 1 and 2 orientations (1 orientation: M = -.39, SD = .78; 2 orientations: M = -1.00, SD = .82; $t_{19} = 3.36$, $p < .01$, Cohen's *d* = .76), but no significant difference between 2 and 4 orientation (2 orientations: M = -1.00, SD = .82; 4 orientations: M = -1.00, SD = .72; $t_{19} = .03$, $p > .05$). This pattern of results suggests that the storage limit for oriented stimuli, while greater than one item, was limited to about two items. Importantly, these results show that when consolidation time was not severely limited people could consolidate more than one item in VSTM, suggesting that the one-item limit we found in the minimum time condition can be ascribed to consolidation rather than storage limitations.

In sum, the minimum time condition suggests that only a single orientation can be consolidated at a time, the hallmark of a strictly serial process. This result is therefore consistent with earlier work suggesting strictly serial consolidation of orientation information (Becker, Miller & Liu, 2013; Liu & Becker, 2013). Finally, the 300 ms condition provided a control which allowed us to demonstrate that once the limit on consolidation time was removed, people could consolidate and store more than one item in VSTM.

Comparison of CDA between Experiments 1 and 2

The CDA results within each experiment conform very well to our predictions, with color showing evidence for parallel consolidation and orientation showing evidence for serial consolidation. To further support the observed difference between features we explicitly compared across the color and orientation experiments. Here we focus on the minimum time condition, because it provided the critical results for testing the consolidation bandwidth. Using data for the minimum time condition from both experiments, we conducted a mixed-factorial ANOVA, with feature (color vs. orientation) as a between-subject factor and set size (1 vs. 2 vs. 4) as a within-subject factor. We found a main effect of set size ($F_{2,76} = 5.14$, $p < .01$, $\eta_p^2 = .12$), but non-significant effect of feature ($F_{1,38} = 2.02$, $p > .05$). The interaction between set size and feature was marginally significant ($F_{2,76} = 2.80$, $p = .067$, $\eta_p^2 = .07$). This marginal interaction is consistent with different CDA profiles for color and orientation established by our within-experiment analyses. While, the interaction did not reach conventional statistical threshold of .05, we note that this is a between-subject comparison, which likely increased variability thereby reducing statistical power. In addition, the analysis included the set size four data, which are not the most diagnostic for distinguishing between parallel and serial consolidation, and could have added additional variability that reduced the power to detect the interaction. To further assess the reliability of this effect, we ran a post-hoc mixed-factorial ANOVA that included only data from set sizes 1 and 2, as these two set-sizes should be the most informative in revealing a different CDA profile (see Fig. 1). This analysis revealed a marginally significant main effect for set size ($F_{1,38} = 3.21$, $p = .08$, $\eta_p^2 = .08$) and a non-significant effect for feature ($F_{1,38} = 1.50$, $p > .05$). Importantly, the interaction between set size and feature was significant ($F_{1,38} = 5.10$, $p < .05$, $\eta_p^2 = .12$). These results thus show that even in a between-subject analysis, there is credible statistical evidence that the CDA amplitude varied differently across set sizes for color and orientation, hence consistent with our within-experiment results.

General Discussion

In the current study, we measured the behavioral accuracy and CDA amplitudes in a masked change detection task to examine the bandwidth of VSTM consolidation. The CDA provides an electrophysiological index of VSTM consolidation that helps resolve the controversy about whether the bandwidth of consolidation depends on the type of information. Specifically, while our previous behavioral work has indicated that the consolidation of color information is a parallel process and the consolidation of orientation information is a serial process, work by others (Rideaux et al., 2015, 2016) has suggested that consolidation is always a parallel process.

The 300 ms exposure condition in both experiments provided a baseline measure of VSTM *storage capacity* under the current experimental settings. In Experiment 1 with color stimuli, the CDA amplitude increased monotonically as the set size increased from set-size one to two and to four. However, in Experiment 2 with orientation stimuli, the CDA amplitude increased from set size one to two but showed no further increase from set size two to four. Previous research has established that the CDA amplitude reflects the number of items held in the memory and it would increase with set size and reach an asymptotic level when the set size reaches the storage capacity (Drew & Vogel, 2008; Ikkai, McCollough & Vogel, 2010; Jost, Bryck, Vogel, & Mayr, 2011; Luck & Vogel, 2013; Luria & Vogel, 2011, 2014; McCollough, Machizawa & Vogel, 2007; Vogel & Machizawa, 2004; Vogel, McCollough & Machizawa, 2005; Woodman & Vogel, 2008). Given the property of CDA and our results in the 300 ms condition, we can infer that VSTM capacity for color is at least three items and its capacity for orientation is at least two items in our experiments. These measurements regarding the VSTM capacity are necessary to ensure the observed limit in consolidation is not due to limits in the storage capacity.

To assess the consolidation bandwidth, we presented the memory array for the minimum time needed to consolidate a single item and varied the set size. In Experiment 1, we found that the CDA amplitude was significantly larger for two colors than one color, but there was no significant difference between two colors and four colors. This suggests that two colors can be consolidated simultaneously but four colors cannot. In Experiment 2, we observed very different results such that the CDA amplitude for all set sizes was equivalent. This result suggests that at minimum time, only one orientation can be consolidated into VSTM. Importantly, these estimates of consolidation bandwidth are lower than the corresponding estimates of the storage capacity, allowing us to attribute the CDA-set size function to limits in consolidation.

The ERP results in the minimum time conditions thus dovetails nicely with previous studies using purely behavioral measures (Becker, Miller, & Liu, 2013; Liu, & Becker, 2013; Mance, Becker & Liu, 2012; Miller, Becker, & Liu, 2014). Both sets of results support the conclusion that consolidating color information is a parallel process with the bandwidth limited to two items, however, consolidating orientation information is strictly serial. Miller, Becker and Liu (2014) explained this difference by hypothesizing that encoding color requires less information than encoding orientation. For example, processing any area on a uniform color patch will suffice to encode its color, whereas encoding the orientation of a grating requires processing of an extended region. This different encoding requirement could lead to a larger bandwidth for color than orientation. The current CDA results further support this notion by providing an electrophysiological correlate of the consolidation bandwidth. However, the precise neural mechanisms for consolidation is unknown. We speculate the difference in consolidation bandwidth for color and orientation is due to differences in the ability to represent multiple features with neural population codes. Further research is necessary to elucidate the neural basis of consolidation bandwidth.

Given our hypothesis that color requires less consolidation resource than orientation, one might expect the a shorter minimum duration thresholds for color than orientation. However, we observed largely similar threshold durations in Experiments 1 and 2. We note that this is not necessarily unexpected, because consolidation could take the same finite amount of time regardless of how much of its bandwidth is consumed. If, however, the number of items exceeds the bandwidth, the consolidation process would need to be completed multiple times. The minimum threshold duration prevents the consolidation process from completing for multiple times, thereby allowing us to measure the number of items that can be accommodated by the bandwidth for different features. The key point is that thresholding procedure only limits the number of iterations that the consolidation process can complete, and therefore is orthogonal to the bandwidth of a single iteration.

Regarding prior results suggesting that orientation information can be consolidated in parallel (Rideaux et al., 2015, 2016), in the Introduction we discussed possible confounds and alternative explanations that may have been responsible for those results. The present CDA results cast further doubts on the notion that all features are consolidated in parallel as we found differences in CDA patterns between color and orientation: while the color pattern is consistent with parallel consolidation, the orientation pattern is consistent with serial consolidation. Thus the present results provide converging evidence for our original explanation, using a method that does not rely on a simultaneous/sequential comparison, but relies on a completely independent measure of the contents of VSTM – the CDA. Even so, it is worth noting that Rideaux et al., provide behavioral evidence that motion direction can be consolidated in parallel. Motion direction is a feature we have not examined, and it is quite possible that motion direction may be consolidated via a parallel mechanism. Thus, it would be interesting to examine consolidation limits of motion direction in future studies using electrophysiological measures. We conclude from the present findings that the bandwidth for consolidation is determined by the stimulus feature.

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Figure captions

Figure 1 *The left two panels are the predicted patterns for the CDA amplitude for the minimum time if consolidation is strictly serial (a) or parallel for two items (b). The diagnostic comparison is whether adding an additional item to the display results in no increase in CDA amplitude (a) or an increase in CDA amplitude (b). The former would indicate only a single item is consolidated, whereas the latter would indicate two items are consolidated. The right panel (c) is the predicted pattern for the 300ms presentation duration where processing time is not limited, thus allowing the consolidation procedure to complete for multiple times. Here the number of items in memory should increase (as indicated by increasing CDA amplitude) until the storage capacity (K) is reached, at which point the pattern should plateau. A second critical diagnostic comparison is that the plateau in panel b should occur earlier than the plateau in panel c. If not, the plateau in panel b could be attributed to limits in the storage capacity rather than limits in the consolidation bandwidth.*

Figure 2 *Experimental procedure used in Main task in Experiment 1.*

Figure 3 *Experimental procedure used in thresholding task in Experiment 1.*

Figure 4 *The results in Experiment 1. (Error bars are estimates of within-subject standard errors following the method of Cousineau (2005).) The behavioral results of minimum time condition and 300 ms condition(a). Difference waves of CDA for arrays of 1, 2 and 4colors of minimum time (b) and 300 ms condition(c) for an averaged two pairs of electrode sites. The mean amplitudes of CDA for minimum time and 300 ms conditions (d).*

Figure 5 *Experimental procedure used in Main task in Experiment 2.*

Figure 6 *Experimental procedure used in thresholding task in Experiment 2.*

Figure 7 *The results in Experiment 2. (Error bars are estimates of within-subject standard errors following the method of Cousineau (2005).) The behavioral results of minimum time condition and 300 ms condition(a). Difference waves of CDA for arrays of 1, 2 and 4colors of minimum time (b) and 300 ms condition(c) for an averaged two pairs of electrode sites. The mean amplitudes of CDA for minimum time and 300 ms conditions (d).*

Fig1

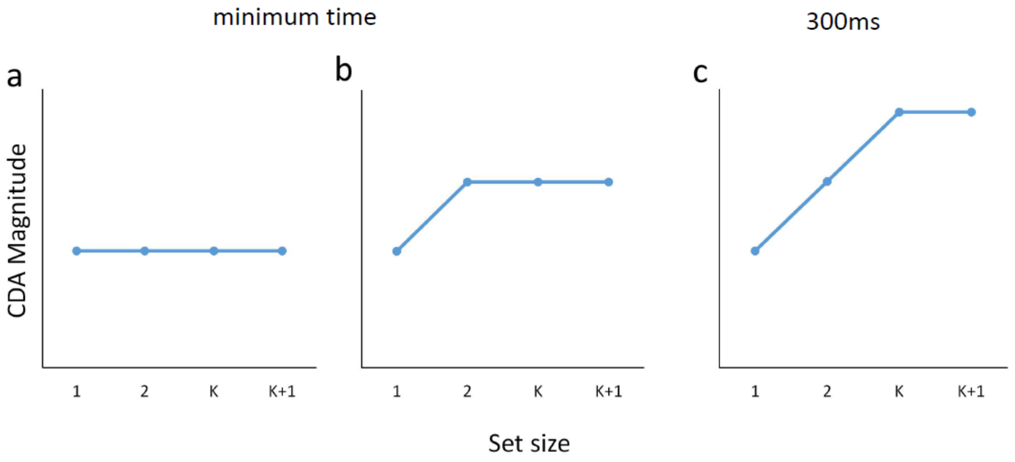

minimum time
300ms
a
b
c
CDA Magnitude
1
2
K
K+1
1
2
K
K+1
1
2
K
K+1
Set size

Fig2

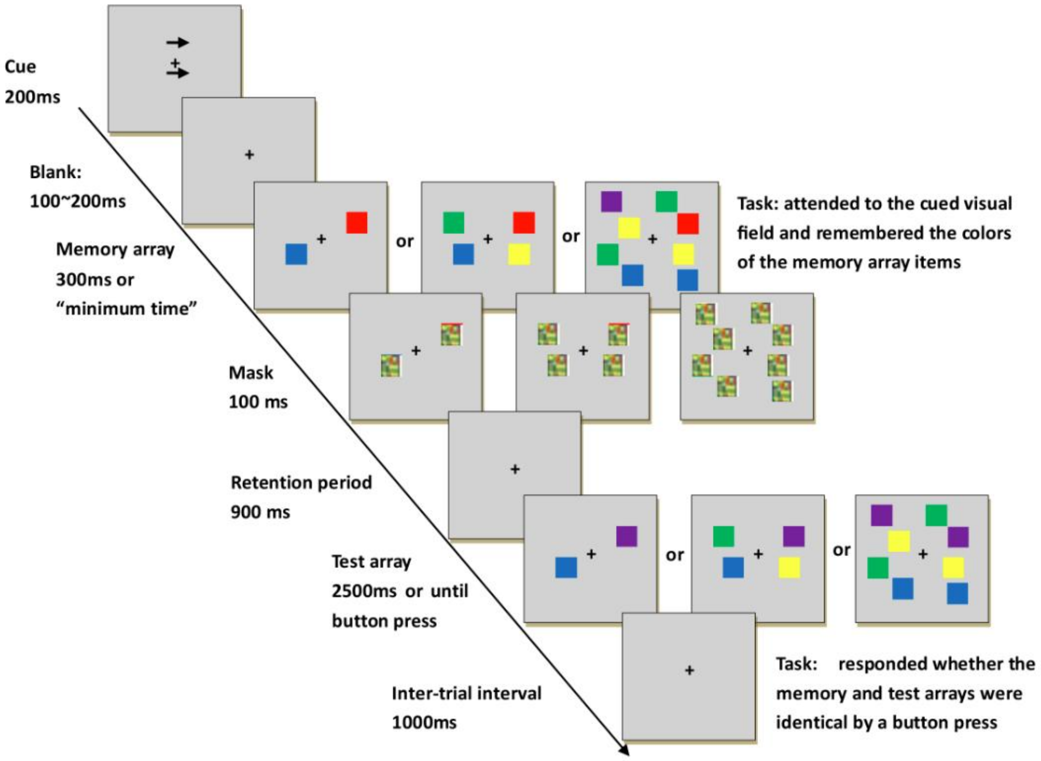

Cue
200ms
Blank:
100~200ms
Memory array
300ms or
“minimum time”
or
or
Task: attended to the cued visual field and remembered the colors of the memory array items
Mask
100 ms
Retention period
900 ms
Test array
2500ms or until button press
or
or
Inter-trial interval
1000ms
Task: responded whether the memory and test arrays were identical by a button press

Fig3

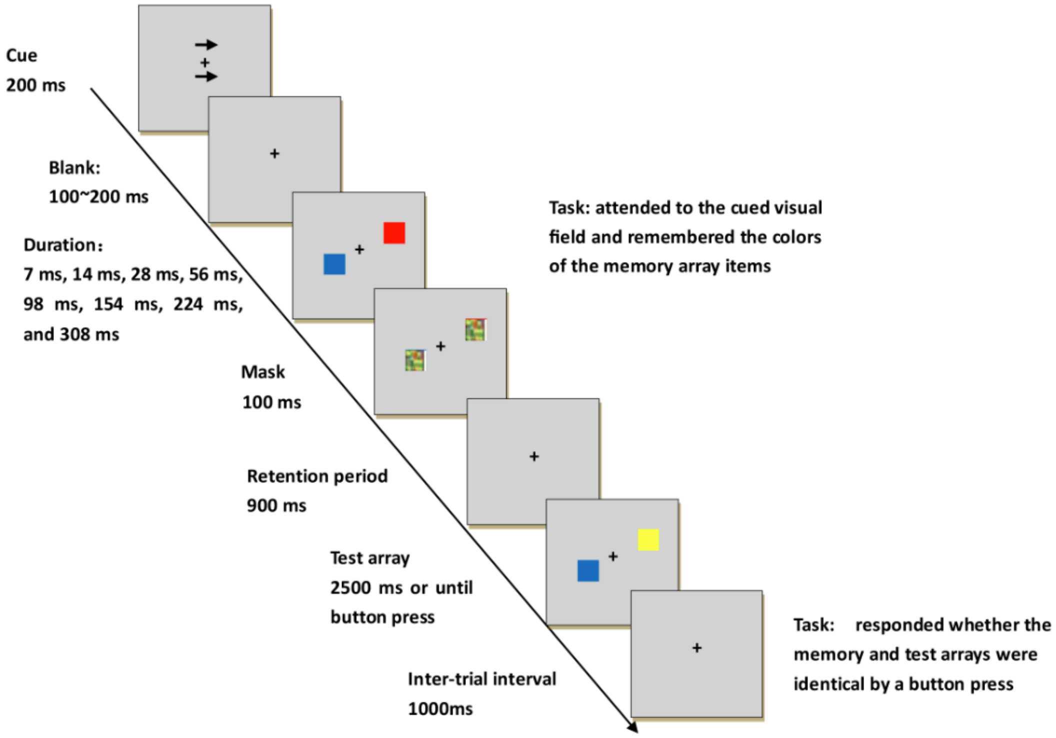

Cue
200 ms
Blank:
100~200 ms
Duration：
7 ms, 14 ms, 28 ms, 56 ms,
98 ms, 154 ms, 224 ms,
and 308 ms
Mask
100 ms
Retention period
900 ms
Test array
2500 ms or until
button press
Inter-trial interval
1000ms
Task: attended to the cued visual
field and remembered the colors
of the memory array items
Task: responded whether the
memory and test arrays were
identical by a button press

Fig4

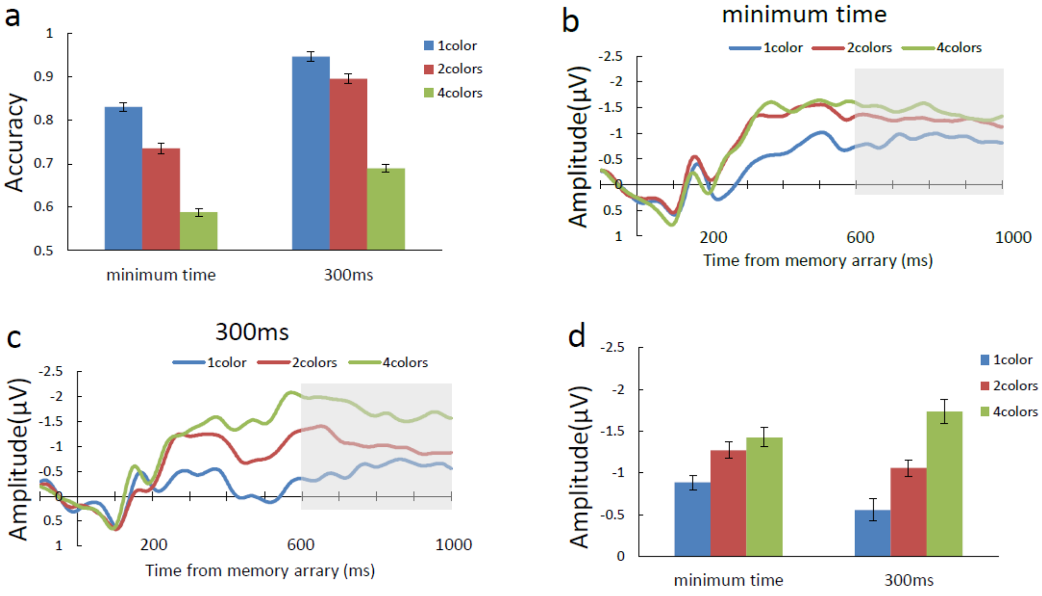

a
Accuracy
1
0.9
0.8
0.7
0.6
0.5
minimum time
300ms
1color
2colors
4colors
b
minimum time
1color
2colors
4colors
Amplitude(μV)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
200
600
1000
Time from memory array (ms)
c
300ms
1color
2colors
4colors
Amplitude(μV)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
200
600
1000
Time from memory arrary (ms)
d
Amplitude(μV)
-2.5
-2
-1.5
-1
-0.5
0
minimum time
300ms
1color
2colors
4colors

Fig5

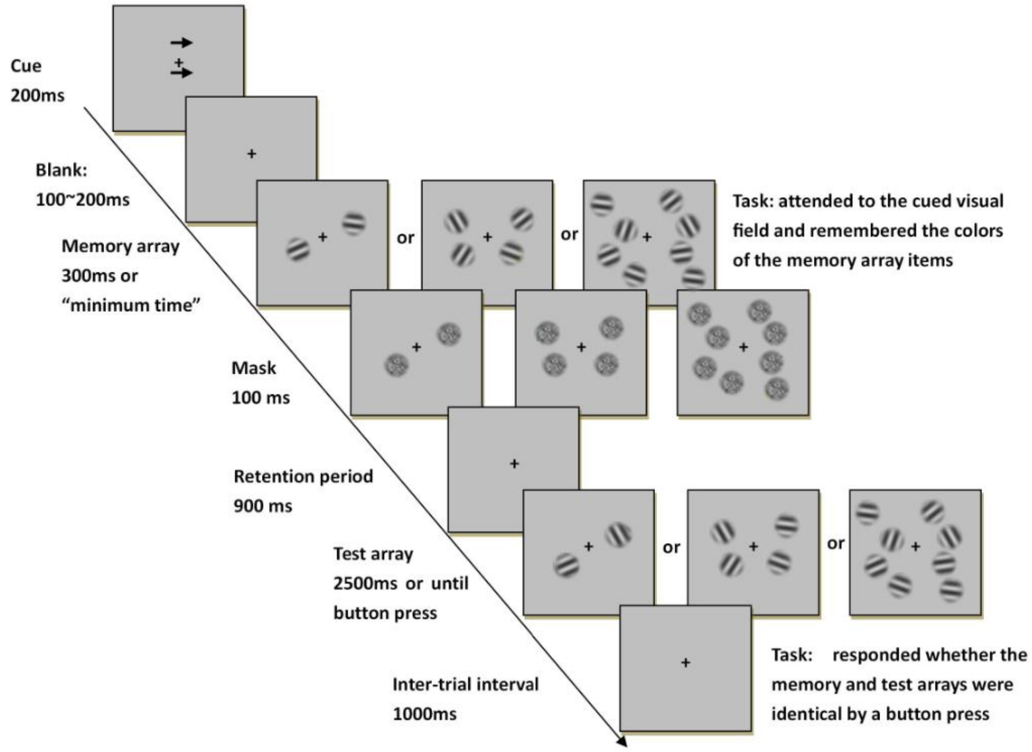

Cue
200ms
Blank:
100~200ms
Memory array
300ms or
“minimum time”
or
or
Task: attended to the cued visual
field and remembered the colors
of the memory array items
Mask
100 ms
Retention period
900 ms
Test array
2500ms or until
button press
or
or
Inter-trial interval
1000ms
Task: responded whether the
memory and test arrays were
identical by a button press

Fig6

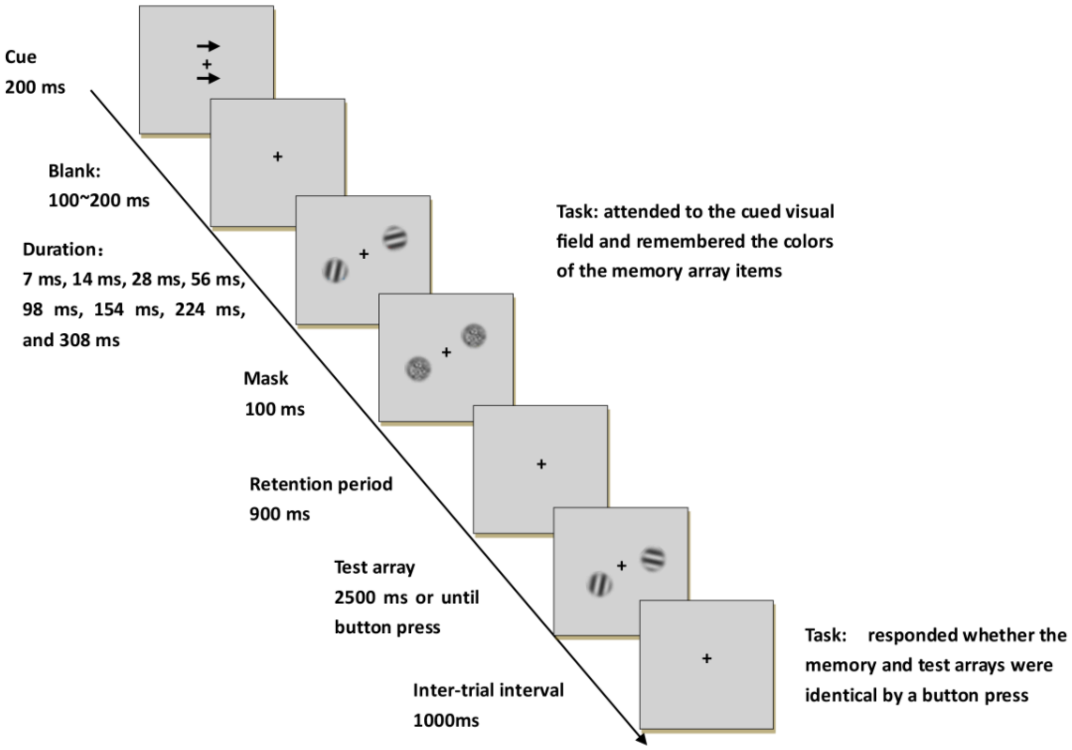
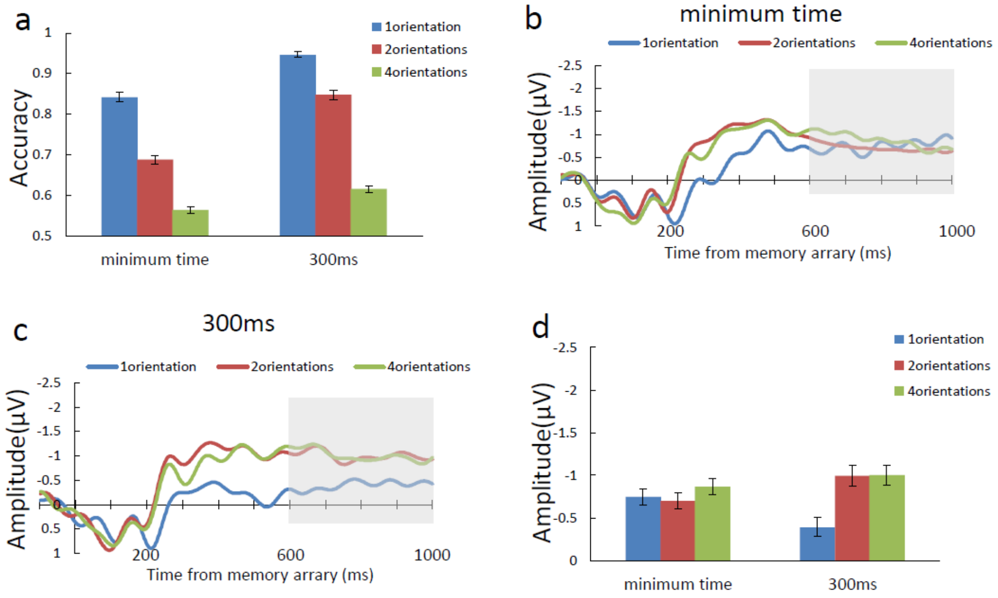

Cue
200 ms
Blank:
100~200 ms
Duration：
7 ms, 14 ms, 28 ms, 56 ms, 98 ms, 154 ms, 224 ms, and 308 ms
Mask
100 ms
Retention period
900 ms
Test array
2500 ms or until button press
Inter-trial interval
1000ms
Task: attended to the cued visual field and remembered the colors of the memory array items
Task: responded whether the memory and test arrays were identical by a button press

Fig7


a
Accuracy
1
0.9
0.8
0.7
0.6
0.5
minimum time
300ms
1orientation
2orientations
4orientations
b
minimum time
1orientation
2orientations
4orientations
Amplitude(μV)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
200
600
1000
Time from memory arrary (ms)
c
300ms
1orientation
2orientations
4orientations
Amplitude(μV)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
200
600
1000
Time from memory arrary (ms)
d
Amplitude(μV)
-2.5
-2
-1.5
-1
-0.5
0
minimum time
300ms
1orientation
2orientations
4orientations

II

VISUAL WORKING MEMORY CAPACITY FOR COLOR IS INDEPENDENT OF REPRESENTATION RESOLUTION

by

Chaoxiong Ye, Lingcong Zhang, Taosheng Liu, Hong Li & Qiang Liu, 2014

PLoS One, 9(3), e91681.
Available online: http://dx.doi.org/10.1371/journal.pone.0091681

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Visual Working Memory Capacity for Color Is Independent of Representation Resolution

Chaoxiong Ye[1], Lingcong Zhang[1], Taosheng Liu[2], Hong Li[3], Qiang Liu[3]*

1 Department of Educational Science and Technology, Minnan Normal University, Zhangzhou, China, **2** Department of Psychology and Neuroscience Program, Michigan State University, East Lansing, Michigan, United States of America, **3** School of Psychology, Liaoning Normal University, Dalian, China

Abstract

Background: The relationship between visual working memory (VWM) capacity and resolution of representation have been extensively investigated. Several recent ERP studies using orientation (or arrow) stimuli suggest that there is an inverse relationship between VWM capacity and representation resolution. However, different results have been obtained in studies using color stimuli. This could be due to important differences in the experimental paradigms used in previous studies.

Methodology/Principal Findings: We examined whether the same relationship between capacity and resolution holds for color information. Participants performed a color change detection task while their electroencephalography was recorded. We manipulated representation resolution by asking participants to detect either a salient change (low-resolution) or a subtle change (high-resolution) in color. We used an ERP component known as contralateral delay activity (CDA) to index the amount of information maintained in VWM. The result demonstrated the same pattern for both low- and high-resolution conditions, with no difference between conditions.

Conclusions/Significance: This result suggests that VWM always represents a fixed number of approximately 3–4 colors regardless of the resolution of representation.

Citation: Ye C, Zhang L, Liu T, Li H, Liu Q (2014) Visual Working Memory Capacity for Color Is Independent of Representation Resolution. PLoS ONE 9(3): e91681. doi:10.1371/journal.pone.0091681

Editor: Luis M. Martinez, CSIC-Univ Miguel Hernandez, Spain

Received September 3, 2013; **Accepted** February 14, 2014; **Published** March 11, 2014

Funding: This study was supported by awards from the National Natural Science Foundation of China (NSFC 31170982) (http://www.nsfc.gov.cn/Portal0/default152.htm). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: lq780614@163.com

Introduction

Visual working memory (VWM) is one of the most prominent mechanisms in human information processing system [1,2]. It provides an online storage for visual information transferred from perceptual processing, which enables us to get a coherent understanding of the visual scene, and it also provides a temporary storage buffer for facilitating extended tasks in daily life [3–5]. Due to its significance, it has received much attention from multiple research fields in the last decade [6–10].

A central issue in this research concerns the capacity of VWM, that is, how much information can be maintained in VWM at one time. It is generally accepted that VWM capacity is quite limited, perhaps to 3–4 object representations [11–16]. Another related issue concerns the resolution of VWM representation, that is, how detailed and precise the memory is with respect to the visual object.

Many behavioral studies have investigated the relationship between VWM capacity and representation resolution [17–21]. The majority of these studies have adopted the change detection task, which requires participants to detect whether or not an object is changed between a memory and a probe array [15,20,22,23]. However, there is a potential problem with the change detection task, in that it involves many processing stages other than storage and maintenance, such as encoding, retrieval or comparison (between the memory and probe arrays). These extra stages of processing could all potentially contribute to the behavioral outcome, thus contaminating the measure of VWM storage and maintenance [24].

One technique to on-line track VWM maintenance without the potential contamination is through the use of event-related potentials (ERP) during the retention interval of a memory task. By these means, researchers have identified an ERP component, contralateral delay activity (CDA) during the retention interval [25], whose amplitude is linked directly with the number of representations maintained in VWM [26–34]. CDA is a large negative wave which is observed over posterior electrode sites contralateral to the locations of the stored objects. It persists throughout the memory retention interval in the change detection task, and is strongly modulated by the number of representations in VWM but reaches an asymptote once capacity is exhausted.

Several ERP studies using the CDA to index memory storage have found an inverse relationship between VWM capacity and representation resolution. For example, Gao et al. [35] found that, when participants maintained low-resolution visual information (e.g., simple basic shapes), the CDA amplitude for 4 objects was higher than that for 2 objects. However, when participants maintained high-resolution visual information (e.g., complex random polygons), the CDA amplitude was equivalent for 2 and 4 objects. This result suggested that VWM capacity was reduced from 4 to 2 as the representation resolution increased. However, in

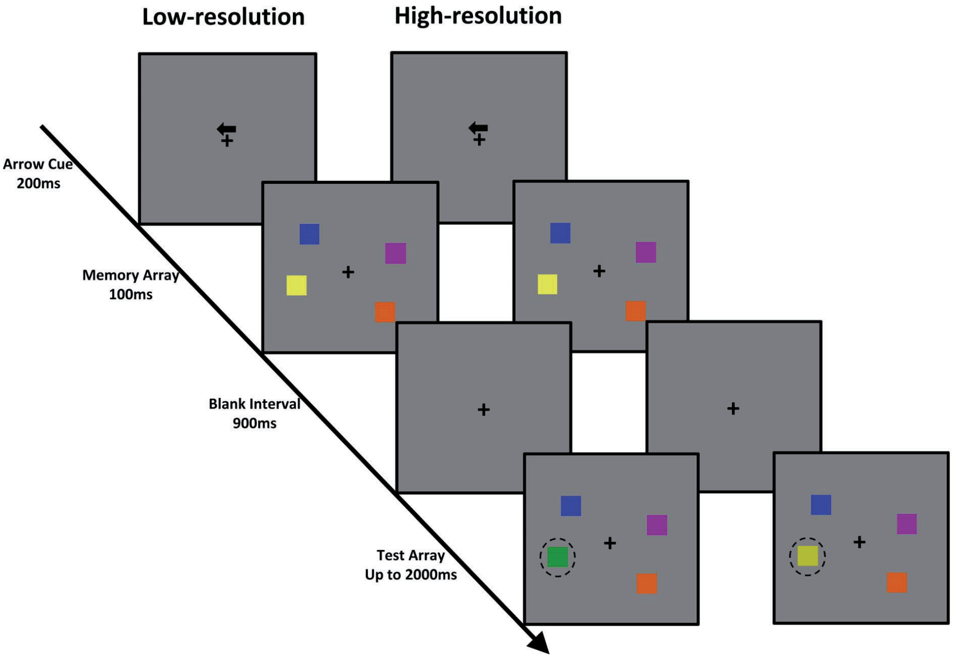

Figure 1. Trial schematic. A low-resolution condition (left) and a high-resolution condition (right) were illustrated. The dashed circle was used to mark the changed item, which was not presented during the experiment.
doi:10.1371/journal.pone.0091681.g001

Gao et al.'s study [35], the complexity of the stimulus and the resolution of the representation co-varied. Thus it is possible that their results were partly due to stimulus complexity instead of the resolution of memory representation. In a further study, Machizawa et al. [36] avoided this potential confound by using the same set of orientation stimuli and manipulated representation resolution by modulating the amount of orientation change between the memory and probe stimuli. They obtained similar findings as Gao et al. [35]: CDA amplitude was higher for 4 than for 2 orientations in the low-resolution condition, but they were equivalent in the high-resolution condition. These results implied that VWM could maintain 1–2 high-resolution representations or 3–4 low-resolution representations, even when both conditions were based on the same visual stimuli(see also ref [37]).

The inverse relationship between VWM capacity and representation resolution has been demonstrated in ERP studies for several visual features, including polygon, Landolt ring, oriented bars and arrows. However, whether this same relationship holds for the color feature is not clear. Color is an important feature for many aspects of visual processing. In addition, color is also widely used in many studies of VWM capacity and resolution [11,13,17,19,26,28,38–41]. Indeed, two previous ERP studies do not support the inverse relationship between VWM capacity and representation resolution for color feature. In one study, Ikkai et al. [39] compared CDA for high-contrast and low-contrast color stimuli in a change detection paradigm. Changes in the high-contrast condition was large while change in the low-contrast condition was subtle, thus presumably relying on low- and high-resolution representations, respectively. They found no difference in CDA amplitude across the contrast conditions, but 4 colors evoked a higher CDA than 2 colors. Similarly, Luria et al. [41]

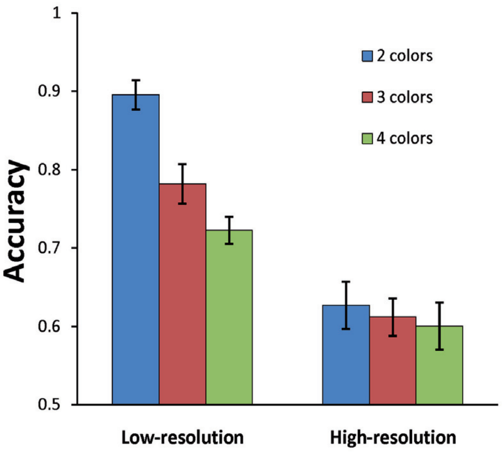

Figure 2. The behavioral results. Error bars show standard error of the mean.
doi:10.1371/journal.pone.0091681.g002

used high-similarity and low-similarity color stimuli and found equivalent CDA amplitudes across the high- and low-similarity conditions.

Although these results suggest that capacity and representation resolution do not have an inverse relationship for the color feature, there were two potential problems with these experiment [39,41]. First, in these studies, the high- and low-contrast (or high- and low-similarity) conditions were based on different visual stimuli. It is known that CDA amplitudes could be different for different stimulus material (orientation and color) with the same number of items [29]. Thus, caution is needed when comparing CDA amplitudes between different colored stimuli. Second, the asymptote of CDA amplitude is a good index to measure the limit of the VWM capacity. In Ikkai et al.'s study [39], they used set sizes of 2 and 4, and in Luria et al.'s study [41], they used set sizes of 2, 4, 6. Although both studies demonstrated that the CDA amplitude for set size 4 was higher than set size 2, it would be possible that the asymptote of CDA amplitude was different between conditions. Such as, in high-contrast (or low-similarity) condition, the CDA amplitude reached an asymptote in 4 items, but, in low-contrast (or high-similarity) condition, it reached an asymptote in 3 items. Here, we wanted to corroborate and extend previous results, while avoiding the above potential problems, so as to further examine the relationship between VWM capacity and representation resolution for the color feature.

In this study, we used a change detection task typically used in ERP research [36], [37,39,41], and measured CDA to index the amount of information stored in VWM. We used colored squares as stimuli and manipulated representation resolution by varying the magnitude of color changes between the memory array and the probe. In the high-resolution condition, the changed probe had a similar color to the stored color. In contrast, in the low-resolution condition, the change between probe color and stored color was highly discriminable. By comparing behavioral performance and ERPs in the low- vs. high-resolution condition, we examined the relationship between VWM capacity and representation resolution for color.

Methods

Participants

Eighteen right-handed students (12 females) from Liaoning Normal University volunteered to participate in this experiment for pay. They reported no history of neurological problems, reported having normal color vision and normal or corrected-to-normal visual acuity. Written informed consent was provided by each participant prior to the experiment. This research was approved by the Research Ethics Committee of Liaoning Normal University of China and was conducted in accordance with the Declaration of Helsinki.

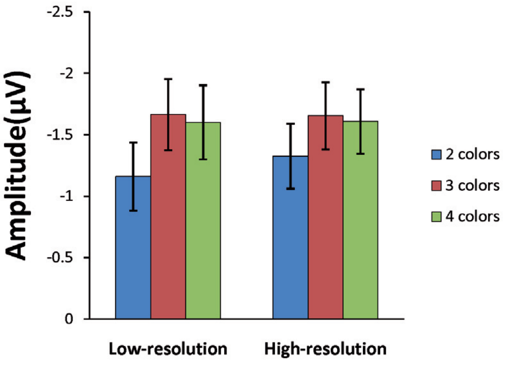

Figure 4. Mean amplitudes of CDA for the low- and high-resolution condition. Error bars show standard error of the mean.
doi:10.1371/journal.pone.0091681.g004

Stimuli

Each memory item was a square (size: 0.65°×0.65°) whose color was chosen randomly without replacement from a set of six highly discriminable colors. RGB values for the six colors were: red [233, 0, 0], green [30, 138, 18], blue [26, 49, 178], orange [210, 85, 7], yellow [231, 228, 66], purple [156, 0, 158]. We refer to these six colors as the *original set*. The probe colors in the high-resolution condition consisted of six colors similar to original set: red [216, 0, 0], green [49, 151, 34], blue [50, 60, 192], orange [226, 93, 25], yellow [216, 214, 50], purple [171, 31, 182]. We refer to these six colors as the *similar set*.

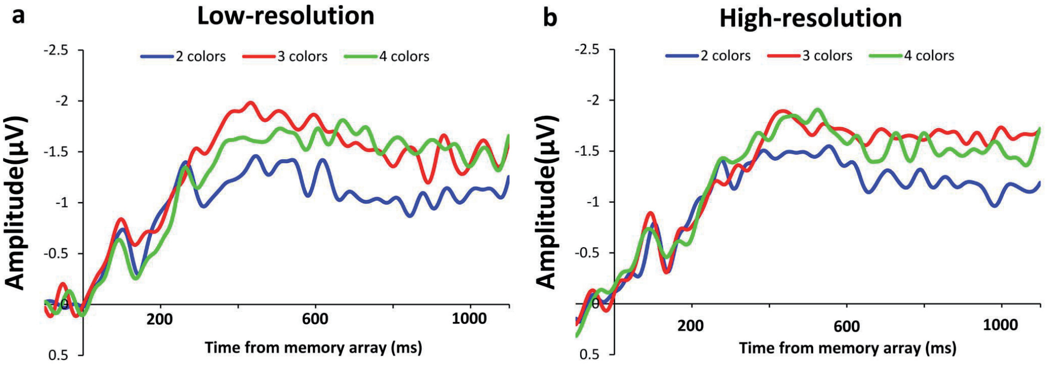

Figure 3. Difference waves of CDA for arrays of 2, 3 and 4 colors in low-resolution (a) and high-resolution (b) conditions. Grand-averaged ERP waveforms were time-locked to the onset of the memory array.
doi:10.1371/journal.pone.0091681.g003

Experiment Design and Procedure

Participants were seated in an electrically shielded and sound-attenuated recording chamber at a distance of 70 cm from a flat cathode ray tube monitor. Items were presented within $4^\circ \times 7.3^\circ$ rectangular regions bilaterally, centered 3° to the left and right of the center of the screen. The memory array consisted of 2, 3, or 4 different colored squares in each hemifield with their colors randomly sampled from a set of 6 possible colors (the original set) with the constraint that any given color would not appear more than once in each hemifield. Stimulus positions were randomized on each trial, with the constraint that the distance between squares within a hemifield was at least 2° (center to center).

Each trial began with a 200 ms arrow cue above a fixation point, followed by a 100 ms memory array, a 900 ms blank period and finally, a 2000 ms probe array (Figure 1). Participants were required to keep their eyes fixated on the fixation while storing the colors in the hemifield indicated by the cue. The probe array in the cued hemifield had one different color than the memory array on 50% of trials; they were identical in the remaining trials. The participant's task was to indicate whether the probe array was identical to the memory array, or a color has changed in the corresponding location between the memory and probe array. We emphasized response accuracy rather than response speed in the instruction. We kept the memory array constant while varying the magnitude of color change between the memory and probe array to manipulate representation resolution. In the low-resolution condition, when a color change occurred, a new color square that was not used in the memory array would be randomly selected from the original set. In the high-resolution condition, a color change would entail presenting a corresponding color from the similar set (e.g., a yellow changed to a different shade of yellow, see Figure 1).

We used a 2 (resolution: high vs. low)×3 (set size: 2 vs.3 vs. 4) within-subject design. The two resolution conditions were blocked and the order of blocks was counterbalanced across participants. There were 200 trials for each set size, with a total of 600 trials per resolution block which were fully randomized. Each block was split into 6 mini-blocks of 100 trials each, with a break of at least 30 s between mini-blocks and 5 min between blocks. The entire experiment lasted approximately 60 min. Before each block, there were at least 20 practice trials to ensure the participants understood the instructions.

Electroencephalography Recording and Analyses

Electroencephalographic (EEG) activity was recorded from 64 tin electrodes mounted in an elastic cap, using the International 10/20 System. Vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG) were recorded with two electrodes, one placed below the left eye, and another placed next to the right eye. Impedance at each electrode site was maintained below 5 k**Ω**. The EEG and EOG were amplified by a QuickAmp amplifier (Brain Products GmbH, Munich, Germany) with a 50 Hz low-pass and were digitized at a sampling rate of 500 Hz.

The EEG was algebraically re-referenced offline to the average of the left and right mastoids during post-recording analyses and segmented into 1100 ms epochs starting from 100 ms before the memory array onset. EEG contaminated with horizontal eye movements greater than 2° (>32 μV HEOG amplitude) were excluded from analysis. Trials with remaining artifacts exceeding ±75 μV in amplitude were rejected. Participants with trial rejection rates that exceeded 25% were excluded from the analyses. Four participants (3 females) were excluded on this basis, such that the results reported below is based on data from 14 participants.

Three pairs of electrode at posterior parietal sites (CP3/CP4, CP5/CP6, and P7/P8) were chosen for analysis based on previous work on CDA [28,35–37]. The contralateral waveforms were computed by averaging the activity recorded at left hemisphere electrode sites when participants were cued to remember the right side of the memory array with the activity recorded from the right hemisphere electrode sites when they were cued to remember the left side. The ipsilateral waveforms were computed by averaging left and right hemisphere sites when participants were cued to remember the left and right side of the memory array, respectively. The CDA was defined by subtracting the ipsilateral activity from the contralateral activity, with a measurement window of 300–900 ms after the onset of the memory array. Following previous work [35,37], the average CDA waveforms were smoothed by applying a 17 Hz low-pass filter, without loss of relevant information, given that the CDA is a sustained low-frequency wave.

Results

Behavioral Data

As shown in Figure 2, consistent with the previous findings [39,41], the accuracy was lower for the high-resolution than for the low-resolution conditions. A two-way ANOVA with set size (2, 3, 4 objects) and resolution condition (low, high) as factors yielded main effects of set size, $F(2, 26) = 51.002$, $p<.001$, and condition, $F(1, 13) = 94.037$, $p<.001$. The interaction between the two factors was also significant, $F(2, 26) = 28.429$, $p<.001$. Separate one-way ANOVAs confirmed that the main effect of set size was only present in the low-resolution condition, $F(2, 26) = 66.603$, $p<.001$, but not in high-resolution condition, $F(2, 26) = 2.135$, $p = .14$. Thus behavioral results suggest that the capacity of VWM suffered a marked reduction in the high-resolution condition.

Electrophysiological Data

Consistent with prior research [26–37,39,41], we observed a CDA that emerged around 300 ms after memory array onset and persisted throughout the retention period. The grand average subtraction waveforms for each set size are shown in Figure 3a for the low-resolution condition and in Figure 3b for the high-resolution condition. Figure 4 shows the mean amplitudes of CDA in both conditions. The CDA amplitudes (for each subject and each condition) were submitted to a two-way ANOVA with set size (2, 3, 4 objects) and resolution condition (low, high) as factors. The only significant effect was that of set size, $F(2, 26) = 7.445$, $p< .01$, which reflected an increase in CDA amplitude as more colors were stored. Post-hoc comparisons showed significant difference in CDA amplitude between 2 and 3 colors in low-resolution, $t(13) = 2.756$, $p<.05$, and high-resolution, $t(13) = 2.892$, $p<.05$, condition, while the amplitude was not significantly different between 3 and 4 colors in either low-resolution, $t(13) = -0.394$, $p = .70$, or high-resolution, $t(13) = -0.366$, $p = .72$, condition. This result suggested that participants maintained approximately 3 colors in both resolution conditions. Importantly, neither the main effect of condition, $F(1, 13) = 0.247$, $p = .63$, nor the interaction between condition and set size, $F(2, 26) = 0.510$, $p = .60$, were significant.

Discussion

The goal of the present experiment is to examine the relationship between VWM capacity and representation resolution for the color feature. To that end, we employed a change detection task with ERP recordings and used the CDA component to index memory storage. Behavioral performance showed a large difference in overall accuracy across the two resolution conditions, demonstrating that our manipulation of resolution demand was effective. However, we observed equivalent CDA amplitude in the low- and high-resolution condition, suggesting that the CDA was not influenced by task difficulty in general. Regardless of the resolution demand of the task, the CDA amplitude for 4 colors was higher than 2 colors but not different from 3 colors. This suggests that VWM always holds a fixed capacity of approximately 3 color representations in both low- and high-resolution conditions. Our results were consistent with Ikkai et al. [39] and Luria et al.'s [41] studies. More importantly, we found that for same memory stimuli, although behavioral accuracy was impaired when high-resolution representations were required, the amplitude and asymptote of the CDA did not change with the need for higher resolution.

Several previous studies have shown that CDA amplitude was not only modulated by the number but also by the encoding level of representation resolution of the memory materials [36,37]. Our results, on the other hand, support the notion that CDA amplitude reflects only the number of items retained in working memory [28], [39], because CDA amplitudes were no different in the low- and high-resolution conditions and reached an asymptote at 3 items in both conditions. There are two leading accounts to explain the upper limit of VWM capacity. According to the slot model, visual working memory has a discrete limit on the number of items it can retain, or a limited number of available working memory "slots". When all slots are filled, no information about additional items is maintained [11,15,16,20,26]. Thus, CDA should increase as more slots are utilized, regardless of the representation resolution. Therefore, in both conditions CDA amplitudes should reflect a fixed upper limit in capacity. According to the resource model, working memory capacity relies on dynamic resources [19,18,42], which can be allocated flexibly to accommodate increasing representation resolution, albeit with less upper limit in terms of capacity. Thus, there should be trade-offs between capacity upper limit and representation resolution, and the capacity upper limit reflected by CDA amplitude should be higher in low-resolution than in the high-resolution condition.

Although previous ERP results using orientation as the memory stimuli largely support the resource model [36,37], Ikkai et al. [39], Luria et al. [41] and our results reject the resource model and provide strong evidence for the slot model. In particular, our results on the asymptote of CDA amplitude stand in contrast to Machizawa et al.'s findings [36], which was obtained under a very similar experimental paradigm. One salient difference between these two sets of studies, Ikkai et al. [39], Luria et al. [41] and our study vs. Machizawa et al. [36] and Gao et al. [37], is the visual stimuli used: whereas the latter studies used boundary objects and oriented stimuli, we and others (Ikkai et al. [39] and Luria et al. [41]) used colors (a surface feature). It is possible that there are genuine differences in processing mechanisms for color and orientation features in VWM. Many recent behavioral studies have shown different performance for color and orientation information in working memory tasks. Stevanovski et al. [43] found that memory in the color condition was significantly better than memory in the orientation condition. Woodman et al. [29] argued that the performance difference for color versus orientation was due to different consolidation rates in VWM, with a faster rate for color than for orientation. Another series of study examining the bandwidth of consolidation also found differences between color and orientation information [44–46]. In particular, consolidation of orientation into VWM is a serial process but the consolidation of color into VWM can occur in parallel for at least two colors. Finally, Alvarez et al. [47] found that there are different codes for objects defined by boundary feature and objects defined by surface features, and that shapes or orientations belong to boundary objects and colors belong to surface objects. Thus, our finding on VWM capacity with color stimuli, consistent with findings using color stimuli but inconsistent with findings using orientation stimuli [36,37,39,41], is plausible given different processing mechanisms for color and orientation information in VWM.

Together, our results and previous results suggest that the relationship between VWM capacity and representation resolution varies for different visual features. For orientation features, capacity and resolution can exhibit trade-off, whereas for color, there is a fixed capacity regardless of resolution demand. Our results caution against generalization of results across visual features in studies of VWM. Future research is needed to probe the mechanisms responsible for the observed difference between color and other features and also to more systematically investigate VWM capacity and resolution for different visual materials.

Author Contributions

Conceived and designed the experiments: QL CY TL. Performed the experiments: CY LZ. Analyzed the data: CY. Wrote the paper: QL CY TL HL.

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III

A TWO-PHASE MODEL OF RESOURCE ALLOCATION IN VISUAL WORKING MEMORY

by

Chaoxiong Ye, Zhonghua Hu, Hong Li, Tapani Ristaniemi, Qiang Liu &
Taosheng Liu, 2017

Journal of Experimental Psychology: Learning, Memory, and Cognition, 43 (10),
1557-1566.
Available online: http://dx.doi.org/10.1037/xlm0000376

A two-phase model of resource allocation in visual working memory

Chaoxiong Ye[a,b], Zhonghua Hu[a], Hong Li[c], Tapani Ristaniemi[b], Qiang Liu[a],

Taosheng Liu[d]

a. Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian, China, 116029

b. Faculty of Information Technology, University of Jyväskylä, Jyväskylä, Finland, 40014

c. School of Education Science, Minnan Normal University, Zhangzhou, China, 363000

d. Department of Psychology, Michigan State University, East Lansing, MI 48824

Running Head: Control of resource allocation in VWM
Number of manuscript pages: 21
Number of tables:0
Number of figures:2

Correspondence to:
Qiang Liu, Ph.D.
Research Center of Brain and Cognitive Neuroscience,
Liaoning Normal University,
Dalian 116029, China
E-mail: lq780614@163.com

Acknowledgements:

This research was supported by grants from the National Natural Science Foundation of China (NSFC 31571123) to Q. L., from the program of China Scholarships Council (CSC201508350054) to C.Y., and from the National Institutes of Health (NIH R01EY022727) to T. L. We thank Drs. Jeffrey Johnson, Wei Ji Ma and an anonymous reviewer for their insightful and constructive comments on an earlier version of this manuscript.

Abstract

Two broad theories of visual working memory (VWM) storage have emerged from current research, a discrete slot-based theory and a continuous resource theory. However, neither the discrete slot-based theory or continuous resource theory clearly stipulates how the mental commodity for VWM (discrete slot or continuous resource) is allocated. Allocation may be based on the number of items via stimulus-driven factors, or it may be based on task demands via voluntary control. Previous studies have obtained conflicting results regarding the automaticity vs. controllability of such allocation. In the current study, we propose a two-phase allocation model, in which the mental commodity could be allocated only by stimulus-driven factors in the early consolidation phase. However, when there is sufficient time to complete the early phase, allocation can enter the late consolidation phase, where it can be flexibly and voluntarily controlled according to task demands. In an orientation recall task, we instructed participants to store either fewer items at high-precision or more items at low-precision. In three experiments, we systematically manipulated memory set size and exposure duration. We did not find an effect of task demands when the set size was high and exposure duration was short. However, when we either decreased the set size or increased the exposure duration, we found a trade-off between the number and precision of VWM representations. These results can be explained by a two-phase model, which can also account for previous conflicting findings in the literature.

Keywords: visual working memory; mental commodity allocation; voluntary; involuntary.

Introduction

Visual working memory (VWM), which could be generally defined as “the active maintenance of visual information to serve the needs of ongoing tasks” (Luck & Vogel, 2013), has been proposed to be a cognitive system that holds a limited amount of visual information in a temporary storage buffer so that it may be quickly accessed, integrated with other information, or otherwise manipulated (Drew & Vogel, 2009). VWM capacity exhibits a stable individual difference and is correlated with measures of higher cognitive function, accounting for 43% of individual differences in global fluid intelligence (Fukuda, Vogel, Mayr, & Awh, 2010), 46% of individual differences in overall performance on a broad battery of cognitive tasks (M. K. Johnson et al., 2013). Furthermore, VWM storage capacity, VWM precision (the resolution of memory representation) and consolidation (the transfer of sensory information into VWM storage) is impaired in people with psychiatric disorders (Fuller et al., 2009; Gold et al., 2010; Zokaei, Burnett Heyes, Gorgoraptis, Budhdeo, & Husain, 2014). Therefore, understanding VWM mechanisms is very important for studies of human cognition.

Two broad theories have been proposed for the nature of mental commodity that supports VWM storage[1], a discrete slot-based theory and a continuous resource theory. The original model of the discrete slot-based theory, often called *classic slot model*, proposes that VWM has a limited number of available “slots”, which store a limited set of discrete, fixed-precision representations (Cowan, 2001; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). When all slots are filled, no information about additional items can be stored, and the memory precision does not vary with the number of items. An updated version of the discrete slot-based theory advances a *slots + averaging model*, which proposes that if the number of to-be-represented items is below the maximum number of slots, then an item can be represented by multiple slots (Zhang & Luck, 2008). The discrete slot-based theory has received support from a number of empirical studies (Barton, Ester, & Awh, 2009; Donkin, Nosofsky, Gold, & Shiffrin, 2013; Rouder et al., 2008; Zhang & Luck, 2011). Alternatively, the other class of theories propose that the mental commodity supporting VWM storage is better described as a type of continuous resource. For example, the *flexible resource model* does not impose an upper item limit, but proposes VWM consists of a pool of resources that can be allocated flexibly to a small number of items to create high-precision representations or distributed among a large number of items to create low-precision representations (P. M. Bays, Catalao, & Husain, 2009; P. M. Bays & Husain, 2008; P. M. Bays, Wu, & Husain, 2011; Huang, 2010; Wilken & Ma, 2004). The fundamental difference between these two classes of theories is whether there exists an upper item limit[2]. Based on this difference, discrete slot-based theory predicts that precision would decrease with an increase in the number of stored items, but the maximum number of items is strictly limited by the number of slots. By contrast, continuous resource-based theory predicts that the monotonic declines should be observable across much larger set sizes without any fixed item limit. Zhang and Luck (2008) used a standard mixture model and found that as the number of items stored in VWM increased from one to three, the VWM precision monotonically declined, but the precision was constant when the memory set size varied from three to six. Although their results supported the discrete slot-based theory, P. M. Bays et al. (2009) used a swap model and found no evidence to support a fixed upper limit on the number of items that can be held in VWM. Another challenge to slots + averaging model was the *variable-precision model*, which was a more recent model of continuous resource theory. This model proposes that the precision of VWM representations varies randomly from trial to trial (Fougnie, Suchow, & Alvarez, 2012; van den Berg, Shin, Chou, George, & Ma, 2012). The debate between the discrete slot-based models and continuous resource models has been intense and is currently still unresolved (Balaban & Luria, 2015; P. M. Bays, 2014; Paul M Bays, 2015; Franconeri, Alvarez, & Cavanagh, 2013; Luck & Vogel, 2013; Vogel & Machizawa, 2004). However, there is a general agreement that the mental commodity of VWM is an allocable resource of limited capacity.

The current debate between these two classes of VWM theories centers on the quantization of the mental commodity, which is not the focus of the present work. Instead, here we investigated how the mental commodity is allocated to store items, regardless of the discrete vs. continuous nature of the mental commodity itself (Suchow, Fougnie, Brady, & Alvarez, 2014). The mechanism of allocation addresses the general question of how people structure and process VWM representations, which is an important aspect of VWM that is not captured by the discrete slots vs. continuous resource debate (Brady, Konkle, & Alvarez, 2011; J. S. Johnson, Simmering, & Buss, 2014; Suchow et al., 2014). Previous studies suggested that there are two possibilities (Machizawa, Goh, & Driver, 2012; Murray, Nobre, Astle, & Stokes, 2012). Allocation may be based on the number of items via stimulus-driven factors, or it may be based on the task demands via voluntary control. We refer to the former as the involuntary allocation hypothesis, which predicts that VWM precision can only be determined by stimulus-driven factors at encoding and will not be affected by task demands. We refer to the latter as the voluntary allocation hypothesis, which predicts that VWM precision can be flexibly and voluntarily controlled according to task demands.

Previous studies have found support for both the involuntary and voluntary hypotheses (Gao, Yin, Xu, Shui, & Shen, 2011; He, Zhang, Li, & Guo, 2015; Machizawa et al., 2012; Murray et al., 2012; Ye, Zhang, Liu, Li, & Liu, 2014). For example, Murray et al. (2012) manipulated payoff schemes to emphasize either the quality or quantity of memory and found no voluntary resource allocation in VWM, supporting the involuntary allocation hypothesis. However, Machizawa et al. (2012) also manipulated the degree of memory precision by task demands and found that people can voluntarily enhance the precision of their VWM, but only for a few items, thus supporting the voluntary allocation hypothesis. To our knowledge, no satisfactory explanations have been offered to reconcile these discrepant findings.

However, the involuntary and voluntary allocation may not be mutually exclusive. We note that the exposure durations used by the above studies supporting involuntary allocation were relatively short, about 25-50 ms/item (He et al., 2015; Murray et al., 2012; Ye et al., 2014). In contrast, the studies supporting voluntary allocation tended to use longer exposure durations, about 100-125 ms/item (Gao, Yin, et al., 2011; Machizawa et al., 2012). Previous work has demonstrated that the length of exposure duration will impact the VWM consolidation (P. M. Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011). In the context of both slot-based and resource-based theories, VWM consolidation and mental commodity allocation are basically equivalent. Here, we propose that consolidation (or mental commodity allocation) contains two different phases. In the early phase (involuntary consolidation phase), mental commodity could be allocated only by stimulus-driven factors to create the initial representation. When the exposure duration is sufficiently long, allocation can enter the late voluntary phase, where allocation could be flexibly and voluntarily controlled according to task demands. Because the consolidation process is itself capacity or bandwidth limited (Becker, Miller, & Liu, 2013; Jolicoeur & Dell'Acqua, 1998; Liu & Becker, 2013; Mance, Becker, & Liu, 2012; Miller, Becker, & Liu, 2014; Vogel, Woodman, & Luck, 2006), whether participants can enter the late voluntary phase depends on the length of consolidation time and the number of memory items. This two-phase allocation model could account for previous discrepant findings.

In the current study, we gave participants instructions and incentives (in points of reward) to strategically control the balance between the number and precision of memory. We tested our model by manipulating exposure duration and set size. We predicted that when participants needed to remember items at a high set-size with a short exposure duration, the mental commodity allocation would still be in the early involuntary consolidation phase, making it impossible to vary VWM precision according to task requirements (Experiment 1). However, when there was enough exposure duration to enter the late voluntary phase, VWM precision variation would be observed either with a smaller set-size (Experiment 2) or with a longer exposure duration (Experiment 3). As we will discuss, these results and the new two-phase allocation model can further reconcile previous conflicting results (Gao, Yin, et al., 2011; He et al., 2015; Machizawa et al., 2012; Murray et al., 2012; Ye et al., 2014).

Experiment 1

In the first experiment, we aimed to test the early, involuntary, phase of mental commodity allocation. Thus we restricted stimulus presentation time such that participants could not enter the late, voluntary, phase. To do this, we needed to select a set-size and exposure duration such that the latter is just short enough to complete the involuntary consolidation of all the items. We chose a set-size of four items and an exposure duration of 200 ms, based on the following considerations: Woodman and

Vogel (2008) estimated that about 100 ms is needed to consolidate one orientation into memory, and our recent work (Becker et al., 2013; Liu & Becker, 2013; Miller et al., 2014) proposed that consolidation for orientation information is a serial process. Therefore, the consolidation time for four orientations would be about 400 ms. Moreover, previous studies found that, without a post mask[3], the visible persistence can still store stimulus information for at least 100 ms to 200 ms after stimulus offset due to retinal persistence (Averbach & Coriell, 1961; Brockmole, Wang, & Irwin, 2002; Coltheart, 1980; Di Lollo & Dixon, 1988). Thus, we adopted a more conservative estimate of the available time for VWM consolidation. Presenting four items for 200 ms is our best estimate of just enough time to complete the VWM involuntary consolidation phase. According to the two-phase allocation model, we expect to find no voluntary VWM precision variation in this experiment.

Methods

Participants

Forty-seven undergraduate students from Minnan Normal University (42 females, 46 right-handed, 19-23 years old) volunteered to participate in this experiment for course credit. They reported no history of neurological problems, reported having normal color vision and normal or corrected-to-normal visual acuity. Written informed consent was provided by each participant prior to the experiment. The study was conducted in accordance with the Declaration of Helsinki and was approved by the ethics committee of Liaoning Normal University.

Visual stimuli

Visual stimuli were generated using MGL (http://gru.stanford.edu/doku.php/mgl/overview), a set of custom OpenGL libraries running in MATLAB (The MathWorks, Natick, MA). The stimuli were sinusoidal gratings (contrast, 0.7; spatial frequency, 3 cycles/deg) in a circular aperture (size, 0.9°) presented on a gray background. The orientation of each stimulus was randomly selected from 90 possible angles evenly spaced from 0° to 180°, with the orientations separated by at least 12°. The edge of the aperture was smoothed such that no sharp change in luminance was present between the gratings and the background. The gratings could be presented in four possible locations, located at the corners of an imaginary square (eccentricity, 3°). A fixation dot (0.2°) was presented in the center of the screen throughout the experiment. The stimuli were presented on a 19'' LCD monitor (1280×768 pixel), and participants viewed the display at a distance of 60 cm in a dark room.

Task and design

Participants were asked to perform an orientation recall task in two precision conditions with the trial structures depicted in Fig 1. Each trial started with the presentation of a fixation dot in the center of the screen. Four oriented gratings were then presented for 200 ms. After a 1000 ms retention period, a location cue (a 1° square outline) appeared in one of the stimuli's location, along with an adjustable probe grating (presented at fixation). Participants adjusted the probe's orientation to match that of the cued grating. Three keys were used to rotate the probe grating (initial orientation was always vertical): two adjustment keys that rotated the probe grating by ±4° per key press. Participant could also move the cursor with the mouse and press the third adjustment key to rotate the probe grating to the cursor position. These parallel ways of adjustment allowed participants to adjust the orientation either finely (by the first two adjustment keys) or coarsely (by the mouse). Participants were told to make adjustments until they were satisfied, at which point they pressed the space bar to finalize their response. Participants were then provided with feedback that contained three values. The first value was "offset", which was the difference between their reported orientation and the actual orientation of the cued grating. The second value was "Score", which showed the number of points participants earned on that trial. The third value was "Total Score", which was the number of points participants had accumulated in the experiment. The next trial started 900-1100 ms after the feedback. In Experiment 1, there are two precision conditions: high-precision and low-precision. The participants were asked to memorize the orientations with different levels of precision. We manipulated the rule of earning points to encourage them using the corresponding memory precision. In the high-precision condition, participants earned 6 points if their offset was smaller than 10° and earned nothing otherwise. In the low-precision condition, participants earned 4 points if their offset was smaller than 30° and earned nothing for offset between 30° and 50°. To encourage participants to store in memory at least some information about every item in the low-precision condition, we penalized them 2 points for offset larger than 50°. In addition, participants received a base score of 100 points at the beginning of the experiment and they were fully informed of the reward rule. At the end of the experiment, the points were converted to a participation grade as part of their course credit.

INSERT FIGURE 1 ABOUT HERE

The two precision conditions were blocked and the order of blocks was counterbalanced across participants. There were 280 trials for each precision block. Each block was split into 7 mini-blocks of 40 trials each, with a break of at least 30s between mini-blocks and 2 min between blocks. The entire experiment lasted approximately 60 min. Before each block, there were at least 20 practice trials to ensure the participants understood the instructions.

Data analysis

Because it might take some time for participants to form the appropriate strategy given the feedback in each precision condition, we did not analyze the first 80 trials in each block such that results were based on the subsequent 200 trials (including the first 80 trials into the analysis did not change the results).

For each trial, we calculated the offset (error) in the recalled orientation by subtracting the participants' orientation setting from the target orientation. We adopted the standard mixture model (Zhang & Luck, 2008) to fit the data using the MemToolbox (Suchow, Brady, Fougnie, & Alvarez, 2013). The standard mixture model assumes that performance on the orientation recall task is determined by a mixture of two types of trials. On a proportion of trials, participants did not consolidate the items into VWM, so they simply guessed, with the reported orientation conforming to a uniform random distribution. On the remaining trials, participants consolidated the item into VWM, which contains a noisy representation of the target orientation, modeled by a von Mises distribution. This allowed us to estimate the number of items stored (K) as well as the precision of the memory representation (SD)[4]. We fit the model to individual participant data in each condition and used paired t-tests to compare the model parameters at the group level to assess statistical significance between conditions. In addition, we also used the swap model and variable-precision model to fit the data of all experiments. These models have been suggested to provide a better description of the data under certain conditions (P. M. Bays et al., 2009; Fougnie et al., 2012). We generally observed highly consistent results no matter which fitting model was used. We report these additional modeling results in the supplemental material 1.

Results and Discussion

Participants earned an average of 714 points in the low-precision condition and 638 points in the high-precision condition. There was no main effect of which condition was encountered first for all dependent measures. We thus combined all participants in the following analysis, regardless of the presentation order.

We averaged parameters of all models for individual fits (Fig. 2a). For both the precision (SD) and the number of items stored (K), there was no significant differences between the low-precision condition and high-precision condition, t(46) = 0.442, p = .661 for SD, , t(46) = 0.200, p =.842 for K. A Bayes factor analysis showed that the null hypothesis (i.e., no difference between the low- and high-precision conditions) was 5.757 times (for SD) and 6.196 times (for K) more likely than the alternative hypothesis (Rouder, Speckman, Sun, Morey, & Iverson, 2009).

These results implied that participants are unable to strategically increase the number of items stored in VWM by reducing the precision of the representations or vice versa.

INSERT FIGURE 2 ABOUT HERE

We observed that participants were unable to trade off number and precision in VWM when exposure duration was short and set-size was large. That is, the mental commodity allocation appeared to be based on stimulus-driven factors, regardless of the task demands. These results validated our choice of set size and exposure duration and supported our prediction that the mental commodity allocation would be in the early, involuntary phase at this set-size and exposure duration. These results were also in line with findings from previous studies using similar settings (He et al., 2015; Murray et al., 2012). Next, we tested whether voluntary control is possible in a later phase of allocation in Experiment 2 and 3.

Experiment 2

According to the two-phase allocation model, when exposure duration is short, reducing the size of memory set should allow the allocation to enter the late phase, where more efficient voluntary control can be exerted. In this experiment, in order to ensure sufficient processing time to complete the early involuntary phase, we reduced the set-size from four to two. Given the estimated consolidation rate of 100 ms per orientation, an exposure duration of 200 ms should be sufficient to complete the early involuntary phase. Hence we expected that memory precision should vary depending on task requirements.

Methods

Participants

A new sample of fifty undergraduate students from Minnan Normal University (42 females, 49 right-handed, 18-23 years old) volunteered to participate in this experiment for course credit. They reported no history of neurological problems, reported having normal color vision and normal or corrected-to-normal visual acuity. Written informed consent was provided by each participant prior to the experiment. The study was conducted in accordance with the Declaration of Helsinki and was approved by the ethics committee of Liaoning Normal University.

Task and design

The design and procedure of Experiment 2 were identical to those of Experiment 1, except that the total number of items in the memory array was reduced to two. On each trial, two gratings were presented in two randomly chosen locations out of the four possible locations.

Results and Discussion

Participants earned an average of 966 points in the low-precision condition and 862 points in the high-precision condition. There was no main effect of which condition is encountered first for all dependent measures.

For the precision parameter (SD), there was a significant difference between the low-precision condition and high-precision condition, t(49) = 7.355, p < .001. But for the number of stored item (K), there was no significant difference between the two conditions, t(49) = 0.681, p = .499 (Fig. 2b). A Bayes factor analysis showed that the null hypothesis was 5.218 times more likely to be true than the alternative hypothesis for K. These results, which were different with Experiment 1, implied that memory precision was higher in high-precision than in low-precision condition but the number of memorized items remained the same across conditions. These results thus implied that participants could enhance the precision in VWM according to tasks demands when the load on consolidation is low.

In addition, we conducted a mixed-factor ANOVA with type III sums of squares by taking precision condition (high- vs. low-precision) as within-subject factor and experiment (Experiment 1 vs. 2) as between-subject factor on the SD and K parameter. For SD, there was a significant main effect of precision, F(1, 95) = 18.933, p < .001, and a significant interaction between precision and experiment, F(1, 95) = 12.916, p < .001, the main effect of experiment is not significant, F(1, 95) = 1.418, p = .237. The ANOVA further supported the conclusion that task demand did not influence memory precision (SD) in Experiment 1 but affected memory precision (SD) in Experiment 2. Furthermore, analyses of simple effects showed that in the high-precision condition, the main effect of experiment was significant, F(1, 95) = 6.20, p < .05, while in the low-precision condition, the main effect of experiment was not significant, F(1, 95) = 0.25, p = .619 for SD.

Another mixed-factor ANOVA for the K parameter only found the main effect of experiment to be significant, F(1, 95) = 35.916, p < .001, with neither the main effect of precision, F(1, 95) = 0.003, p = .954, nor the interaction between precision and experiment, F(1, 95) = 0.194, p = .661, reaching significance.

These results implied that when the set-size was two, participants can strategically control the precision of the memorized orientation. We found that set-size is the key factor responsible for the disparate results between Experiments 1 and 2. That is, reducing the number of memory items allow participants to exert voluntary control on mental commodity allocation. This is consistent with predictions of the two-phase allocation model.

Experiment 3

As explained in the Introduction, another prediction of the two-phase mental commodity allocation model is that, when exposure duration is long enough, the allocation will be able to enter the voluntary phase, even at a larger set-size. Thus, in Experiment 3, we used the same procedure as Experiment 1 but extended the exposure duration of the memory items from 200 ms to 500 ms, and tested whether the precision and number of items could be traded off in VWM.

Methods

Participants

A new sample of forty-nine undergraduate students from Minnan Normal University (41 females, 47 right-handed, 19-23 years old) volunteered to participate in this experiment for course credit. They reported no history of neurological problems, reported having normal color vision and normal or corrected-to-normal visual acuity. Written informed consent was provided by each participant prior to the experiment. The study was conducted in accordance with the Declaration of Helsinki and was approved by the ethics committee of Liaoning Normal University.

Task and design

The design and procedure were identical to those of Experiment 1, except that we increased the exposure duration of the memory array to 500 ms.

Results and Discussion

Participants earned an average of 770 points in the low-precision condition and 682 points in the high-precision condition. There was no main effect of which condition was encountered first for all dependent measures.

For the precision parameter (SD), there was a significant difference between the low-precision and high-precision condition, $t(48) = 6.177$, $p < .001$. For the number of stored items parameter (K), there was also a significant effect of precision condition, $t(48) = 5.478$, $p < .001$ (Fig.2c). The results suggested that in the high-precision condition, participants maintained higher resolution memory representations but fewer memory items than in the low-precision condition.

In addition, we conducted a mixed-factor ANOVA with type III sums of squares by taking precision condition (high- vs. low-precision) as within-subject factor and experiment (Experiment 1 vs. Experiment 3) as between-subject factor on the SD and K parameter, respectively. For SD, there was a significant main effect of precision, $F(1, 94) = 24.014$, $p < .001$, a significant interaction between precision and experiment, $F(1, 94) = 18.625$, $p < .001$, but the main effect of experiment was not significant, $F(1, 94) = 1.158$, $p = .285$. The ANOVA further supported the conclusion that task demand did not influence memory precision in Experiment 1 but affected memory precision in Experiment 3. Furthermore, analyses of simple effects showed that the main effect of experiment was significant in the high-precision condition, $F(1, 94) = 8.18$, $p < .01$, but was not significant in the low-precision condition, $F(1, 94) = 1.77$, $p = .187$.

For K, the ANOVA showed that the main effect of precision was significant, F(1, 94) = 16.006, p < .001; the interaction between precision and experiment was also significant, F(1, 94) = 18.159, p < .001; but the main effect of experiment was not significant, F(1, 94) = 0.820, p = .367. These results again supported the conclusion that task demand did not influence memory number (K) in Experiment 1 but affect memory number (K) in Experiment 3. Furthermore, simple effects analyses showed that the main effect of experiment was not significant in the high-precision condition, F(1, 94) = 0.70, p = .406, but it was significant in the low-precision condition, F(1, 94) = 5.64, p < .05.

Here we again observed variations for both number and precision in VWM. As predicted by the two-phase model, these results demonstrated that the exposure duration is the key factor for entering the voluntary phase. For four memory items, more time is needed to enter the late, voluntary, phase, such that the quality and quantity of memory representation can be controlled.

General Discussion

The goal of the present study is to examine whether the memory mental commodity allocation is a hybrid of both voluntary and involuntary processes. We used a point reward system to differentially bias participants to store either high- or low-precision memory representations. In Experiment 1, we did not find any variation for either number or precision in VWM across conditions, indicative of an involuntary phase of mental commodity allocation. In Experiment 2, we adopted the same procedures as Experiment 1, but reduced the total number of items in the memory array from four to two. Here, we found memory precision was modulated by our reward manipulation but the number in VWM remained constant across conditions. In Experiment 3, we adopted the same procedures as Experiment 1, but increased the exposure duration from 200 ms to 500 ms. Here, we found higher memory precision and fewer memorized items in the high-precision condition than the low-precision condition. The results from Experiments 2 and 3 confirm that there is indeed a flexible commodity allocation in VWM by voluntary control, when sufficient time allows participants to enter the voluntary phase of allocation.

Since we found that participants set SD and K strategically in response to the task demands of Experiment 2 and 3, it is natural to ask whether this strategic adjustment allowed them to obtain more rewards. Under the standard mixture model, we can derive expected rewards with a particular combination of (K, SD) values and our reward rule. In Supplemental Material 2, we present this derivation and show that the observed (K, SD) combination in both Experiments 2 and 3 led to a higher expected reward in their respective conditions (high- vs. low-precision) than the alternative (K, SD). However, an exception was observed in the low-precision condition in Experiment 2, where we found had participants used the (K, SD) combination observed under high-precision condition they will obtain a higher reward. However, this can be explained by the limited benefits due to strategic adjustment, caused by the small under-capacity set size (see more details of discussion in Supplemental Material 2). Thus, the voluntary adjustment of mental commodity allocation in response to different payoff schemes does on average lead to a higher reward. This finding is thus consistent with the suggestion that humans can perform probabilistic computations to maximize reward under certain task scenarios (Ma & Jazayeri, 2014).

A two-phase model of mental commodity allocation in VWM

We propose that mental commodity allocation is a hybrid of involuntary and voluntary process, with the voluntary allocation occurring after the involuntary allocation. In the involuntary phase, participants have to first consolidate each item by allocating a small amount of mental commodities (one slot or a small amount of resource) to create some low-resolution representations. Only after the completion of this involuntary phase, can they re-allocate the mental commodities voluntarily according to the task demand. From a cognitive processing point of view, voluntary allocation requires top-down control, which presumably takes extra processing time. In studies of selective attention, for example, it is known that it takes more time to deploy top-down attention than bottom-up attention (Jonides, 1981; Liu, Stevens, & Carrasco, 2007; Muller & Rabbitt, 1989; Pinto, van der Leij, Sligte, Lamme, & Scholte, 2013). From an information theoretical point of view, the involuntary phase can maximize the storage of information with little cost of control, thus providing an efficient mechanism for consolidation. From an ecological point of view, this arrangement also makes sense. When we first encounter a visual scene, it seems beneficial to sample as much information as possible, to detect potentially important objects. An automatic, involuntary process would be suitable for such a sampling purpose. This view is in line with Liesefeld, Liesefeld, and Zimmer (2014)'s findings that participants first have to process all items to a certain degree before they determine whether any irrelevant items are present. Interestingly, a recent study proposed that when a new item is encountered in the environment, it can gain access to VWM automatically without the need for executive resources (Allen, Baddeley, & Hitch, 2014), thus also lending support to our current proposal of the involuntary phase.

After the completion of this involuntary phase, participants should be able to consolidate more visual information for readjusting mental commodity allocation according to task demands. Such reallocation requires participants to use either free mental commodities (if available at the end of the involuntary phase) or release some mental commodities for reallocation among items (when all of the mental commodities have been used at the end of the involuntary phase). In both cases, memory precision for items that are represented by more mental commodities will be improved. Furthermore, this kind of storage likely needs to acquire new information from either the physical stimuli or their visible persistence, as simply duplicating information by existing representations should not increase the informational content, hence the precision, of the memory. Because visible persistence decays rapidly over time, voluntary allocation would need longer stimulus duration than involuntary allocation. We have thus manipulated stimulus duration in our experiments and interpreted our findings in terms of consolidation of VWM representation. However, traditional consolidation studies tended to use post masks while manipulating stimulus-mask interval (Fuller et al., 2009; Fuller, Luck, McMahon, & Gold, 2005; Vogel et al., 2006). This raises the question of whether our effects could be due to differential amount of attention during perceptual encoding stage, which presumably precedes memory consolidation. We did not use masks because that would likely interfere with the mental commodity reallocation process we intended to study (see Footnote 3). Furthermore, had participants been able to strategically allocate differential amount of attention to items during encoding, by, for example, attending to fewer items in the high-precision condition, similar to what a “zoom-lens” model of attention would predict (Eriksen & St James, 1986), they should be able to trade off the number and precision of memory in Experiment 1. The absence of such trade-off suggests that our results are due to the later consolidation stage, rather than encoding. More studies are needed to further examine the flexibility of both the encoding and consolidation stage.

We would like to point out that the two-phase model is compatible with both the slot-based and resource-based theories of VWM. In the first phase, each item is stored with less mental commodities (slots or resources) as a result of rapid and effective consolidation; this process may not consume all the mental commodities. This can explain the results of Experiment 1. After the basic consolidation, mental commodity allocation become more flexible, such that resources could be prioritized to fewer items, which improves memory precision, but with a concomitant cost to other items. Thus, it is easy to understand that participants could reallocate their mental commodities voluntarily in Experiments 2 and 3. Importantly, both theories accept that mental commodities can be focused on a smaller number of items to improve precision. Thus our two-phase model is generally compatible with both slot- and resource-based theories.

Accounting for other results in the literature with the two-phase process

The two-phase model can also account for previous results on this topic. First, we would like to reiterate that if the memory array is presented briefly, not all of items can be consolidated. Under such conditions, memory performance may reflect a limit in consolidation instead of storage capacity. Indeed, we recommended 100 ms per item as the exposure duration when investigating VWM capacity based on our studies on VWM consolidation (Miller et al., 2014). Thus, it is worth noting that previous studies that found no trade-off between memory precision and number tended to use shorter exposure times than our recommended time. According to the two-phase model, participants are still engaged in the involuntary phase of mental commodity allocation at brief exposure times, hence no trade-off is possible.

On the one hand, Murray et al. (2012) used 200 ms exposure duration with four items, and Zhang and Luck (2011) used 200 ms exposure duration with four or six items (Murray et al., 2012; Zhang & Luck, 2011). Neither study observed trade-off in memory precision vs. number under various incentive instructions. Furthermore, in an ERP experiment that used the contralateral delay activity (CDA) to index the amount of information maintained in VWM (Luria, Balaban, Awh, & Vogel, 2016; Vogel & Machizawa, 2004),we used 100 ms exposure duration (with two to four items) and manipulated memory precision by asking participants to detect either a salient change (low-precision) or a subtle change (high-precision) in color. We found that the precision manipulation did not influence memory capacity, i.e., no trade-off between precision and number in VWM (Ye et al., 2014). Recently, He et al. (2015) also used 200 ms exposure duration (with two and four items) and replicated our results in similar experiments (He et al., 2015).

On the other hand, in Machizawa et al. (2012)'s study, where participants remembered two items at 200 ms exposure duration, it is possible that they have finished the involuntary phase and entered the voluntary phase where they could allocate more mental commodities to one item to raise the representation precision (Machizawa et al., 2012). Similarly, in Gao, Yin, et al. (2011)'s study, where participants remembered four items at 500 ms exposure duration, participant likely had enough time to consolidate all items into VWM, so they could have entered the voluntary phase (Gao, Yin, et al., 2011). Under this explanation, previous studies supporting the involuntary mental commodity allocation were likely caused by a lack of consolidation time, even though participant are able to allocate the mental commodities by voluntary control after the involuntary phase.

Although our results are generally in line with these previous studies, our study goes beyond these studies in that it offers a new model, i.e., the two-phase mental commodity allocation model, to reconcile discrepant findings from these studies. Our new model is based on new data obtained under better experimental control than previous studies. Our experiments were conducted with the same procedure using identical stimuli, allowing us to make direct comparisons across experiments. In addition, most of these prior studies adopted the change detection task and thus can only indirectly infer how memory precision changed based on a single accuracy measure of performance (He et al., 2015; Machizawa et al., 2012; Murray et al., 2012; Ye et al., 2014). In our study, we used an orientation recall task and performed quantitative model fitting to separately assess the probability that a memory was stored and the precision of the memory. We can thus directly observe the change in memory precision, going beyond the coarse measures obtained with the change detection task. Thus, our study offers further opportunity to systematically examine individual differences and the detailed mechanisms of mental commodity allocation.

Is the first phase mandatory?

An open question is whether participants could bypass the first phase and go directly to the second in some special conditions. Based on our results, it seems that the involuntary phase could not be avoided. However, it might be possible to shorten the time cost of first phase in some cases. For instance, if a pre-cue indicates one location before the memory items appear, participants could use attention to only encode the item at the cued location. They would only need to allocate mental commodity involuntarily to one item, which would take less time to complete. Since ERPs can provide a measure of stimulus-related processing with a high temporal resolution, future study could consider to use ERP component such as CDA, LPC (late positive component), which was believed to be related to the maintenance of working memory and reflect the top-down control activity of the PFC over the posterior regions (Gao, Xu, et al., 2011; Li, Li, & Luo, 2006), as the index to test this possibility.

Predictions of the two-phase model

Although the two-phase model can accommodate results in the current literature, one may wonder whether it can make novel predictions. We think the two-phase model can lead to a counterintuitive prediction, which is that when participants are asked to remember many items with high resolution, they would create more representations at short stimulus exposure duration than at long exposure duration. This is because participants would involuntarily allocate mental commodities to each item in the first involuntary phase, but reallocate the mental commodities to less complex items to create the high resolution representations in the second voluntary phase. This prediction is counter to the standard effect that memory rate increases as exposure duration prolongs (P. M. Bays, Gorgoraptis, et al., 2011). This prediction seems to have been supported by a recent ERP study. Gao, Ding, Yang, Liang, and Shui (2013) used the CDA component as a neural marker and asked participants to remember two and four complex shapes in different exposure duration conditions (100 ms vs. 500 ms). They observed that CDA was higher for four complex shapes than two complex shapes at 100 ms exposure duration, yet this difference vanishes at 500 ms exposure duration. They suggested that participants could remember three to four items at short exposure durations, but only one to two items during long exposure durations. These results are thus in broad agreement with the two-phase model. However, more direct evidence, as well as more thorough investigation of the time course of allocation is needed to further test this prediction in future studies.

Summary and Conclusion

In summary, our results support the notion that mental commodity allocation during VWM is a two-phase process. Participants initially allocate mental commodities via an involuntary consolidation process in a stimulus-driven mode, after which they could allocate mental commodities via voluntary control according to the task requirements.

Note

1. Here we use the neutral term *mental commodity*, following Suchow et al. (2014)'s to indicate the slots of slot-based theory or the resource of resource-based theory.
2. In addition to the previous models, there is another hybrid model of discrete slot-based theory and continuous resource theory called *bounded resource model*, which proposes a flexible continuous resources pool as well as a maximum number of how many items can be stored (Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007; Suchow et al., 2014).
3. In general, the use of masks to control stimulus exposure time would have been a more rigorous approach in experimental design. But we know that masks can disrupt the consolidation process for memory items. One recent study found that in a recall task even the object-substitution masking can cause degradation in the precision of VWM representation (Harrison, Rajsic, & Wilson, 2015). We did not use masks because if the early phase of commodity allocation is involuntary, masks themselves can be consolidated into VWM, which was irrelevant information and would increase noise in our data.
4. The standard mixture model has two parameters, guess rate (G) and mnemonic precision (SD). The K value is calculated by multiplying the set size with the probability of memory encoding (i.e., 1- G).

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Figure 1.

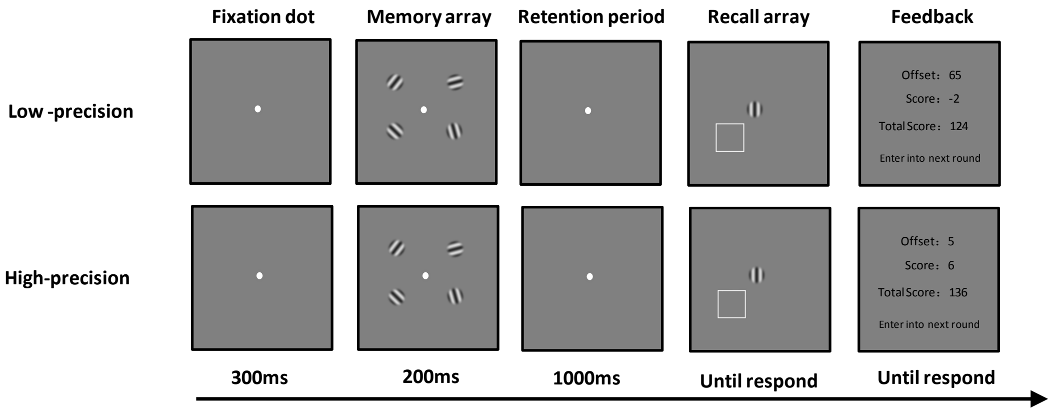

Fig.1 *Trial structure of Experiment 1. A low-precision condition (top row) and a high-precision condition (bottom row) were illustrated.*

Figure 2.

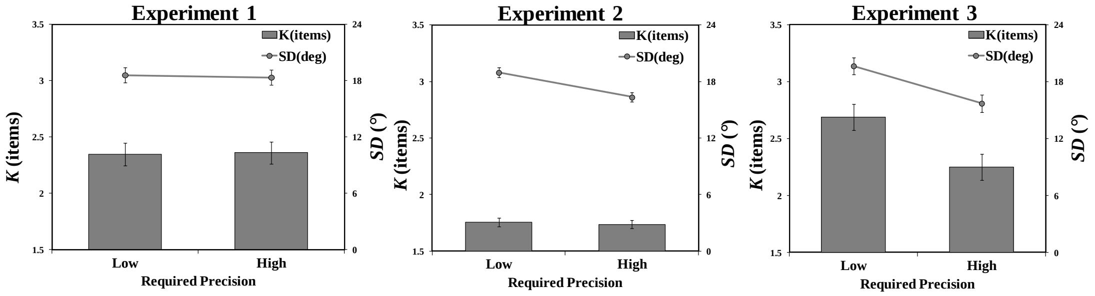

Fig.2 *The results of Experiment 1(a), 2(b) and 3(c), which each experiment in a column. The standard deviation (SD) and the mean number of items stored in memory (K) are plotted separately for the low-precision and high-precision conditions. Error bars are standard error of the mean.*

Supplementary Materials

The data fitting results of swap model

We also use the swap model (Bays, Catalao, & Husain, 2009) to fit our data by using Memtoolbox (Suchow, Brady, Fougnie, & Alvarez, 2013). The swap model assumes that besides the two types of trials in the standard mixture model, there was a third trial type in which participants reported the non-target orientation. The swap model has three parameters, guess rate (G_s), non-target reported rate (B_s) and mnemonic precision (SD_s). This also allowed us to estimate the correct memory rate (P_s) by calculated the probability of correct reporting (i.e., $1 - G_s - B_s$). Data analysis was performed using the MemToolbox (Suchow et al., 2013). Respectively for the high capacity group and low capacity group, we fit the swap model to individual participant data in each condition. We used the SD_s as the memory precision index, and used the P_s as the memory number index.

Experiment 1

We averaged parameters of all models for individual fits in Experiment 1 (Table 1). The results are found in Figure 1. For the precision index (SD_s), a two-way ANOVA with precision condition (low precision vs high precision) and VWM capacity (low VWM capacity vs high VWM capacity) as factors yielded no significant main effects of precision condition [$F(1,24) = 0.645$, $p = .430$, $\eta^2 = 0.026$], and VWM capacity [$F(1,24) = 0.014$, $p = .906$, $\eta^2 = 0.001$]. The interaction between the two factors was also not significant [$F(1,24) = 0.204$, $p = .656$, $\eta^2 = 0.008$].

For the memory number index (P_S), a two-way ANOVA with precision condition (low precision vs high precision) and VWM capacity (low VWM capacity vs high VWM capacity) as factors yielded no significant main effects of precision condition [$F(1,24) = 0.051$, $p = .823$, $\eta^2 = 0.002$], and VWM capacity [$F(1,24) = 1.596$, $p = .219$, $\eta^2 = 0.062$]. The interaction between the two factors was also not significant [$F(1,24) = 2.263$, $p = .146$, $\eta^2 = 0.086$].

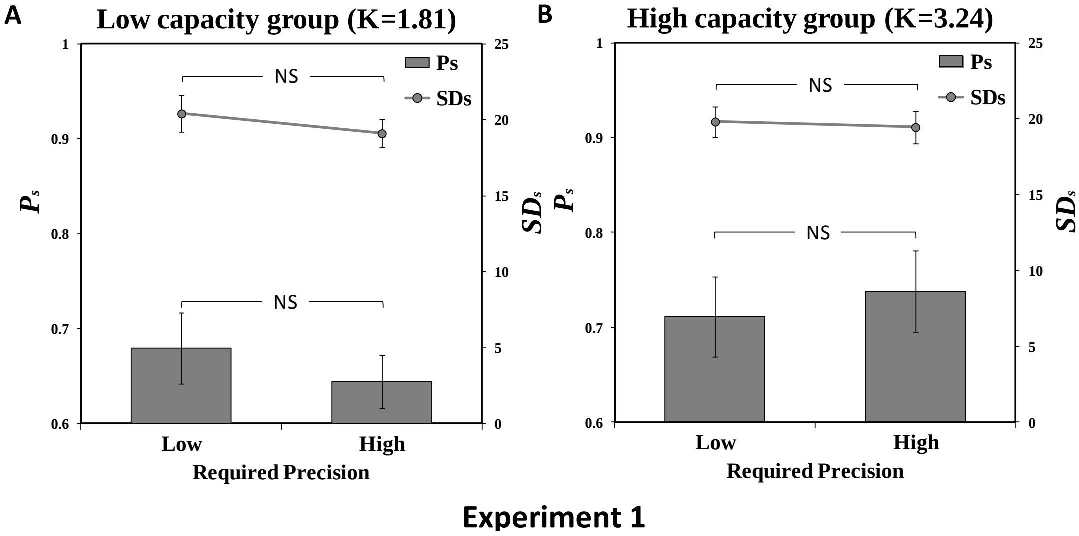

Fig.1 *The swap model fitting results for the low- and high-capacity groups in Experiment 1. The graph on the left (A) shows the low-capacity group's results, with the mean correct memory rate (left) and the standard deviation (right) presented separately for the low-precision and high-precision conditions. The graph on the right (B) shows the high-capacity group's results, which the mean correct memory rate (left) and the standard deviation (right) presented separately for the low-precision and high-precision conditions. Error bars are standard error of the mean.*

Table 1. Experiment 1: Data columns represent mean of memory precision (SD_s), mean of non-target reported rate (B_s), mean probability of random responses (G_s) and mean

probability of correct reporting (P_s).

Experiment 1	High-capacity group				Low-capacity group			
Condition	SD_s	B_s	G_s	P_s	SD_s	B_s	G_s	P_s
High precision	19.45 (3.79)	0.03 (0.04)	0.23 (0.17)	0.74 (0.16)	19.11 (3.32)	0.03 (0.04)	0.32 (0.12)	0.64 (0.10)
Low precision	19.82 (3.61)	0.06 (0.09)	0.23 (0.15)	0.71 (0.15)	20.41 (4.37)	0.06 (0.09)	0.26 (0.13)	0.68 (0.13)

The error terms, in parentheses, reflect the within-subjects standard deviation.

Experiment 2

We averaged parameters of all models for individual fits in Experiment 2 (Table 2). The results are found in Figure 2. For the precision index (SD_s), a two-way ANOVA with precision condition (low precision vs high precision) and VWM capacity (low VWM capacity vs high VWM capacity) as factors yielded a significant main effect of precision condition [$F(1,24) = 13.816$, $p < .001$, $\eta^2 = 0.365$], but no significant main effect of VWM capacity [$F(1,24) = 0.696$, $p= .413$, $\eta^2 = 0.028$]. However, the interaction between the two factors was significant [$F(1,24) = 8.622$, $p < .01$, $\eta^2 = 0.264$].

For the memory number index (P_s), a two-way ANOVA with precision condition (low precision vs high precision) and VWM capacity (low VWM capacity vs high VWM capacity) as factors yielded a significant main effect of VWM capacity [$F(1,24) = 4.450$, $p < .05$, $\eta^2 = 0.156$], but no significant main effect of precision condition

[F(1,24) = 1.806, p = .192, η^2 = 0.070]. However, the interaction between the two factors was significant [F(1,24) = 4.384, p < .05, η^2 = 0.154].

Post-hoc comparisons showed that, in the high-capacity group the memory precision of high-precision condition is higher than of low-precision condition [t(12) = 4.748, p < .001, Cohen's d = 0.94 for SD_s], and the memory number of high-precision condition is less than of low-precision condition [t(12) = 2.485, p < .05, Cohen's d = 0.47 for P_s]. In contrast, in the low-capacity group there was no memory precision difference and memory number difference between high-precision and low-precision condition [t(12) = 0.547, p = .594, Cohen's d = 0.09 for SD_s; t(12) = 0.519, p = .613, Cohen's d = 0.06 for P_s].

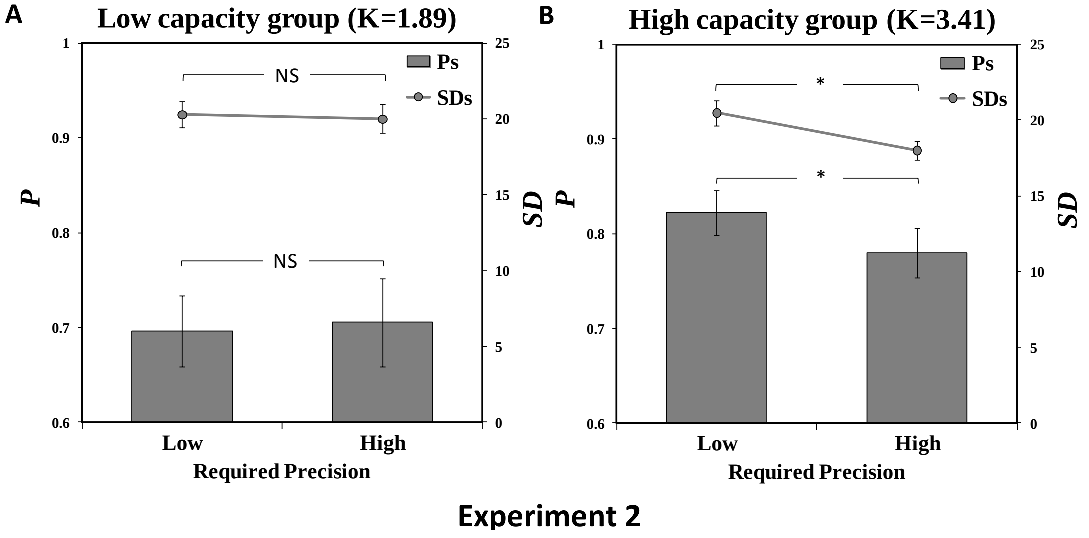

Fig.2 *The swap model fitting results for the low- and high-capacity groups in Experiment 2. The graph on the left (A) shows the low-capacity group's results, with the mean correct memory rate (left) and the standard deviation (right) shown separately for the low-precision and high-precision conditions. The graph on the right (B) shows the high-capacity*

group's results, with the mean correct memory rate (left) and the standard deviation (right) shown separately for the low-precision and high-precision conditions. Error bars are standard error of the mean.

Table 2. Experiment 2: Data columns represent mean of memory precision (SD_s), mean of non-target reported rate (B_s), mean probability of random responses (G_s) and mean probability of correct reporting (P_s).

Experiment 2	**High-capacity group**				**Low-capacity group**			
Condition	SD_s	B_s	G_s	P_s	SD_s	B_s	G_s	P_s
High precision	18.00 (2.21)	0.07 (0.06)	0.15 (0.11)	0.78 (0.09)	20.01 (3.47)	0.03 (0.04)	0.26 (0.17)	0.71 (0.17)
Low precision	20.48 (2.96)	0.06 (0.05)	0.12 (0.11)	0.82 (0.09)	20.30 (3.10)	0.06 (0.04)	0.25 (0.14)	0.70 (0.14)

The error terms, in parentheses, reflect the within-subjects standard deviation.

The goodness-of-fit comparison between the standard mixture model and swap model

For the data of Experiment 1, we compared the goodness-of-fit of the standard mixture model and swap model. We computed the AICc, a measure of goodness-of-fit with a penalty for each additional parameter, separately for each model, participant, and precision conditions. Although a lower mean AICc was found for the swap model (Fig. 3), when we looked at the individual participants separately, we found that, the standard mixture model was most likely for 75% participants and the swap model was most likely for 25% participants. Since the outcomes from statistical tests of mixture model parameters and swap model parameters are essentially identical, our results are robust regardless of the choice of models.

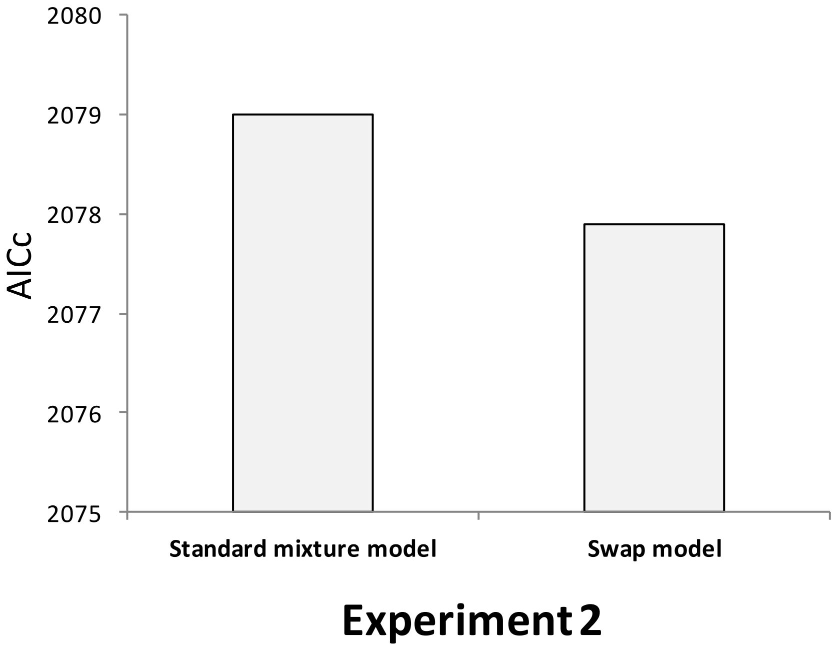

Fig.3 *Average AICc fit measures of the standard mixture model and swap model for the data of Experiment 1.*

For the data of Experiment 2, we compared the goodness-of-fit of the standard mixture model and swap model. We computed the AICc, a measure of goodness-of-fit with a penalty for each additional parameter, separately for each model, participant, and precision conditions. Although a lower mean AICc was found for the swap model (Figure. 4), when we looked at the individual participants separately, we found that, the standard mixture model was most likely for 52% participants and the swap model was most likely for 48% participants. Since the outcomes from statistical tests of mixture model parameters and swap model parameters are essentially identical, our results are robust regardless of the choice of models.

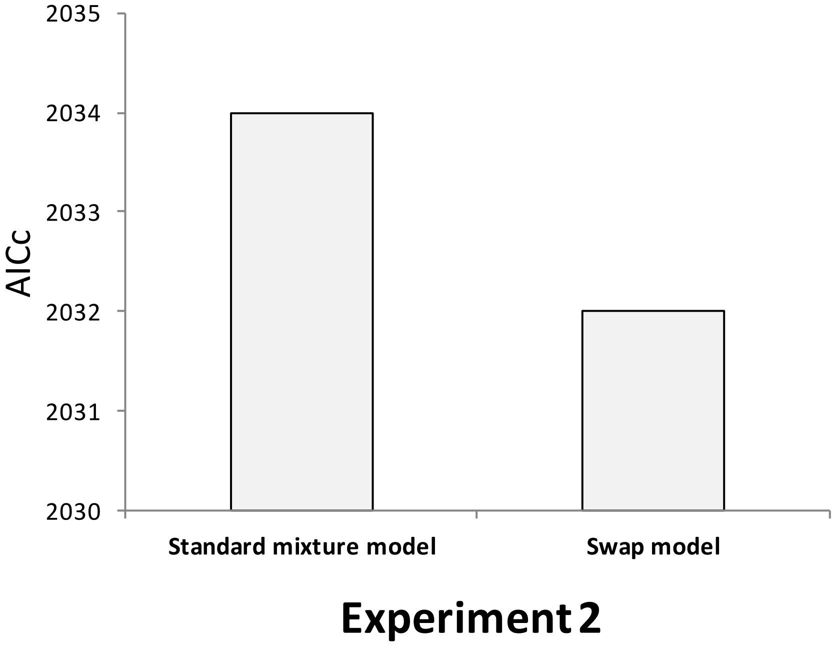

Fig.4 *Average AICc fit measures of the standard mixture model and swap model for the data of Experiment 2.*

In Ye et al. (2017)'s study, they found that the mixture model could best fit the data for most participants, whereas in the present study, both the mixture model and the swap model can better fit the data for part of participants respectively. This may be caused by the difference in the memory materials, we used color stimuli instead of orientation stimuli in this study. Previous studies showed that individual consolidate color stimuli in a parallel way, but consolidate orientation stimuli in a serial way (Becker, Miller, & Liu, 2013; Liu & Becker, 2013; Mance, Becker, & Liu, 2012; Miller, Becker, & Liu, 2014). For some participants, the parallel consolidation may cause higher swap rate, thus the swap model could fit the data better. In contrast, for the participants who did not swap the VWM representation, the swap model will force some of guess trial to be classified as the swap component, thus the mixture model fitted the data better. However, regardless of the choice of models, our results are robust to support a same conclusion.

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IV

THE IMPACT OF VISUAL WORKING MEMORY CAPACITY ON THE RESOURCE ALLOCATION IN CONSOLIDATION

by

Chaoxiong Ye, Hong-Jin Sun, Qianru Xu, Tapani Ristaniemi, Pertti Saariluoma,
Fengyu Cong & Qiang Liu, 2018

Submitted manuscript

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V

THE BILATERAL FIELD ADVANTAGE EFFECT IN MEMORY PRECISION

by

Yin Zhang, Chaoxiong Ye, Debi Roberson, Guang Zhao, Chengbo Xue & Qiang Liu, 2018

Quarterly Journal of Experimental Psychology. 71(3), 749-758.
Available online: http://dx.doi.org/10.1080/17470218.2016.1276943

Original Article

QJEP

Quarterly Journal of Experimental Psychology
2018, Vol. 71(3) 749–758

DOI: 10.1080/17470218.2016.1276943
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The bilateral field advantage effect in memory precision

Yin Zhang[1], Chaoxiong Ye[2], Debi Roberson[3], Guang Zhao[1], Chengbo Xue[1] and Qiang Liu[1]

Abstract

Previous research has demonstrated that visual working memory performance is better when visual items are allocated in both left and right visual fields than within only one hemifield. This phenomenon is called the bilateral field advantage (BFA). The BFA is thought to be driven by an enhanced probability of storage, rather than by greater precision. In the present experiments, we sought to test whether the BFA can also extend to precision when the parameters of the task are modified. Using a moderate number of to-be-remembered items and 400 ms presentation time, we found better precision in the bilateral condition than in the unilateral condition. The classic BFA was still found in the form of an enhanced probability of storage, when presentation time was 200 ms. Thus, the BFA appears to convey both enhanced precision and greater probability of storage. The BFA is most likely due to the allocation of more attentional resources, when items are presented in both left and right visual fields.

Keywords

Bilateral field advantage; Memory precision; Visual working memory

Received: 6 July 2015; accepted: 12 December 2016

Visual working memory (VWM) is usually defined as an online workspace where information can be effectively accessed and updated when a visual stimulus disappears (Luck, 2008). Although its capacity appears limited, individual differences in VWM are significantly correlated to performance on complex cognitive tasks (Hollingworth & Luck, 2009; Jonides et al., 2008; Luck & Vogel, 2013). VWM has been found to explain 43% of the variance in fluid intelligence across individuals (Fukuda, Vogel, Mayr, & Awh, 2010), as well as 46% of the variance across individuals in performance on general cognitive tasks (Johnson et al., 2013). In addition, a variety of mental disorders are often accompanied by reduced working memory capacity and longer memory consolidation times (Fuller et al., 2009; Gold et al., 2010; Karatekin & Asarnow, 1998; Lee et al., 2010). Thus, it is important to understand the role of VWM in both normal and abnormal cognition.

Delvenne (2005) used a standard change-detection paradigm to examine the capacity of VWM, in which squares were presented either in a single hemifield (unilateral condition) or across both visual hemifields (bilateral condition). The squares reappeared after a blank screen of 1000 ms. Participants were asked to detect a change in the spatial location of one item. Performance was better in the bilateral condition than in the unilateral condition. This phenomenon was named the bilateral field advantage (BFA). A BFA has also been found in other cognitive tasks that involve visual encoding processes, such as visual search (Alvarez & Cavanagh, 2005), visual enumeration (Delvenne, Castronovo, Demeyere, & Humphreys, 2011; Railo, 2014), face recognition (Keyes & Brady, 2010), and so on. Notably, Alvarez and Cavanagh (2005) found that the number of objects that could be tracked in a bilateral condition was double that in the unilateral condition, demonstrating that attentional tracking capacity in left and right hemifields is relatively independent.

Since the change detection paradigm includes different stages of visual processing, the BFA for VWM found by

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[1] Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian, China
[2] Department of Computer Science and Information Systems, University of Jyvaskyla, Jyvaskyla, Finland
[3] Department of Psychology, University of Essex, Colchester, UK

Corresponding author:
Qiang Liu, Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian, China 116029.
Email: lq780614@163.com

Delvenne (2005) might arise from the initial encoding of visual information rather than at the memory maintenance stage (Pashler, 1988; Umemoto, Drew, Ester, & Awh, 2010; Woodman & Vogel, 2008). To examine whether the BFA occurs in the maintenance stage, Umemoto et al. (2010) conducted a further study. In Experiment 1, they used an orientation recall task in which two teardrop-shaped stimuli or simple lines, sequentially presented in different orientations, were displayed unilaterally or bilaterally. Following a retention period, a randomly oriented stimulus was presented. Participants' task was to adjust the gratings using a computer mouse to match the orientation of the previously presented stimulus held in memory. Relative to the unilateral condition, there were smaller recall errors in the bilateral condition, even for sequential presentation. In order to test whether this BFA derives from an increased number of items stored or from the precision with which items were stored, they used a recall paradigm and measured both the number and the precision of the stored items in Experiment 2. They increased set size to four and found that the bilateral distribution of information affected the number of items that could be held in VWM, but not their precision.

However, it is difficult to explain how the bilateral condition would convey advantages only in terms of the number rather than the precision of stored items. According to the two main theories of visual working memory, there should be a trade-off between the number of items retained and the precision of those items in VWM. Slot-based models propose that visual working memory has a limited number of available "slots" in which a limited set of discrete, fixed-precision representations are stored (Cowan, 2001; Luck & Vogel, 1997). When all slots are filled, no information about additional items can be stored, and the memory precision does not vary with number of items. If the number of to-be-represented items is below the maximum number of slots, then an item can be represented by multiple slots (Zhang & Luck, 2008). Thus, the precision of memory items could be increased only when the number of items is within the capacity. Alternatively, resource-based models propose that memory resources can be divided up between items flexibly, without a limit to the number of items that can be stored. Thus, the precision with which an item can be retrieved is contingent upon the quantity of resources allocated (Bays, Catalao, & Husain, 2009; Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011; Bays & Husain, 2008). One thing the two theories have in common is that they predict an item/precision trade-off when the number of memoranda is relatively low (e.g., fewer than 4 items). Consistent with the theory, there is robust evidence that memory precision decreases as the number of items to be remembered increases (Barton, Ester, & Awh, 2009; Bays & Husain, 2008; Gorgoraptis, Catalao, Bays, & Husain, 2011; Vogel & Machizawa, 2004).

Given a trade-off between the number and precision of stored items, if bilateral distribution of information affects the number of items held in VWM, it should also affect memory precision, especially when the number of items is low. The reason Umemoto et al. (2010) did not observe a difference of memory precision between bilateral and unilateral conditions could be that they asked participants to remember too many items. The limited memory resources available for a large number of stored items might lead to such poor precision for all items that a statistically significant difference of memory precision between bilateral and unilateral conditions might not be observable.

In the present study, we used a recall procedure similar to the one employed by Umemoto et al. (2010), but optimized to explore whether a bilateral field advantage also arises in memory precision. To accomplish this, we used a moderate number of memory items and sufficient presentation time. Specifically, we asked participants to remember only two items per trial to ensure that set size is lower than the point at which working memory precision reaches asymptote (Anderson & Awh, 2012; Anderson, Vogel & Awh, 2013; Zhang & Luck, 2008). In terms of presentation time, we choose 400 ms for presenting two items, which would allow more time for encoding each item than the 500 ms presentation time for remembering four items that was used in Umemoto et al. (2010)'s study. Our working hypothesis is that, with the number of memory targets set to two, each item might be assigned more available resources in both the bilateral and unilateral conditions. Thus every item should obtain enough resources, so the probed item's performance should not vary in terms of the probability of storage, but only in memory precision.

Experiment 1

Method

Participants. Nineteen right-handed college students, with normal colour vision and normal or corrected-to-normal visual acuity (13 female), from Liaoning Normal University, took part in the study. Each participant in Experiment 1 were paid ¥10 for participation and gave written informed consent. The methods for this study were approved by the Research Ethics Committee of Liaoning Normal University.

Stimuli. Visual stimuli were produced by MGL (http://gru.brain.riken.jp/doku.php?id=mgl:overview), a set of custom OpenGL libraries running in MATLAB. The orientation stimuli were sinusoidal gratings with 0.7 contrast and spatial frequency of 3 cycles per degree, in a circular aperture (size, 0.9°), which appeared on a background of grey (48.4 cd/m^2). The edges of the stimuli were smoothed, and no sharp change in luminance was present between the grating and the background. The gratings were presented

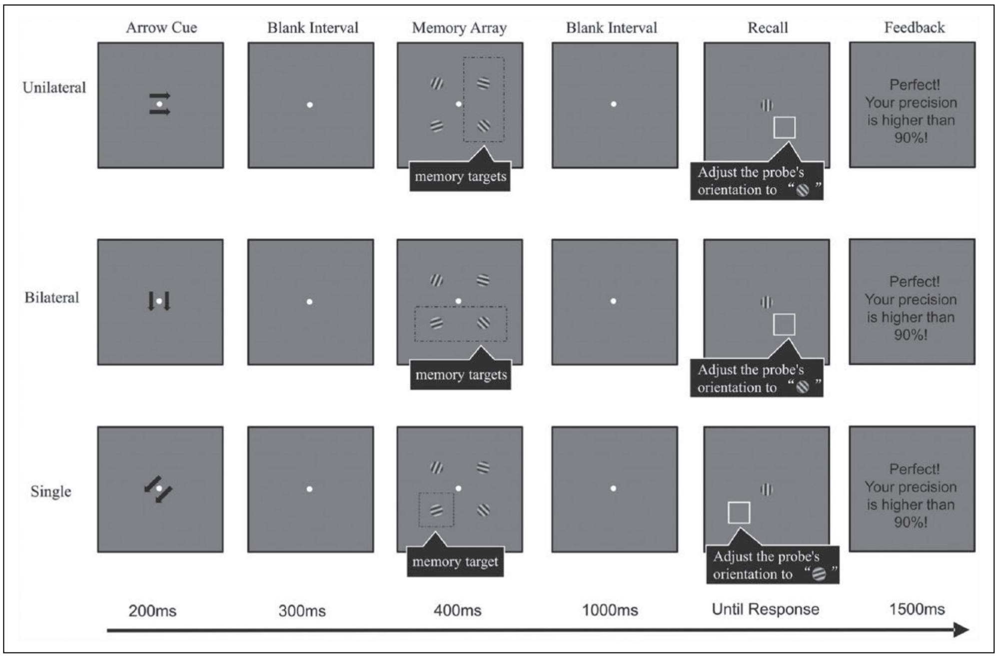

Figure 1. Schematic of Experiment 1 trial structures for each condition. Eight different arrows randomly cued subjects' memory. The "right" and "left" cues make up the unilateral condition; the "up" and "down" cues make up the bilateral condition; and the "lower left", "upper-left", "upper-right", and "lower right" cues make up the single condition.

at four corners of an invisible square (eccentricity, 3°). A fixed point (0.2°) was presented in the centre of the screen throughout our experiment. Each stimulus appeared on a CRT monitor (800×600 pixels, 144-Hz refresh rate, with linearized luminance levels), and subjects viewed the screen at a distance of 60 cm in a dim room. Participants were told to keep their eyes focused on the fixed centre point throughout the experiment.

Procedure. Each trial began with a 200 ms arrow cue, followed by a 300 ms blank screen, a 400 ms memory array, a 1000 ms blank screen, a probe array presented until a response was recorded, and finally 1500 ms of feedback (see Figure 1). There were eight possible directions for the arrows in the cue ("left", "lower left", "upper-left", "right", "lower right", "upper-right", "up", "down"), indicating which region of the array to remember. Participants only needed to remember one or two targets. For example, if the cue was "up", "right", "down", or "left" then participants needed to remember two targets, and if the cue was "lower left", "upper-left", "lower right", or "upper-right" then participants only needed to remember one target (see Figure 1). In all conditions, a square outline appeared after the 1000 ms blank period in the location of one stimulus. Participants rotated the orientation of the probe grating, which was always presented at the screen centre, to reproduce that of the cued grating. Three mouse buttons were applied to adjust the vertical probe grating: one rough adjustment key, for rotating the probe by a free angle, and two meticulous adjustment keys ± 1° per key press. A subsequent trial would not start until participants were satisfied with the adjustments they had made and pressed the space key to receive feedback.

The grating's orientation was random, with the constraint that two gratings presented in the array had at least a 10° gap. Before the gratings appeared, eight different arrow cues appeared randomly. Every condition had 120 trials, for a total of 360 trials across nine blocks of 40 trials each. Before the experiment started, participants practised for at least 20 trials. The whole experiment lasted about one hour.

Data analysis. For each trial, we calculated the difference between the recalled orientation and the cued grating orientation. Fitting the offset data using the mixture model first proposed by Zhang and Luck (2008), we separately measured the storage probability (guessing rate, *g*) and precision (standard deviation, *SD*) of the responses. Data

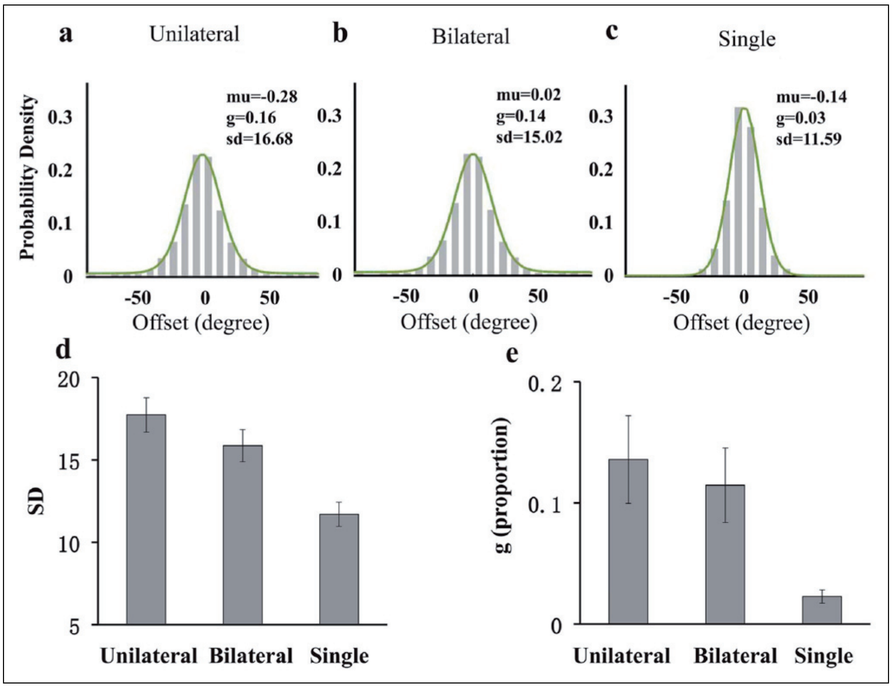

Figure 2. Model-fit results from Experiment 1. Histograms in the top row show probability density functions for the response offsets in (a) the unilateral condition, (b) the bilateral condition, and (c) the single condition. The mean standard deviation (*SD*) and guess rate (*g*) are also shown for each condition. Graphs in the bottom row (d–e) show average values for the two parameters from individual-level data fits in each of the three conditions. Error bars indicate ± 1 standard error of the mean.

analysis was performed using the Mem Toolbox (Suchow, Brady, Fougnie, & Alvarez, 2013). We fitted each individual's data separately using the mixture model and then averaged all participants' guessing rates and *SD*s separately across different conditions, and ran one-way repeated measures analysis of variance (ANOVA) with three levels (bilateral, unilateral, single) for each result parameter (Figures 2a–2c). The *p* values of the main effects and interactions were corrected using the Greenhouse–Geisser adjustment.

Results

Consistent with our predictions, we found evidence for the BFA in precision. For the precision parameter (*SD*; Figure 2d), a significant main effect of display, $F(2, 36) = 34.03$, $p < .001$, $\eta_p^2 = .654$, was revealed by repeated measures ANOVA. The *SD* for the bilateral condition was significantly lower than that for the unilateral condition, $t(18) = 2.64$, $p < .02$, Cohen's $d = 0.42$. The single condition was significantly lower than the bilateral condition, $t(18) = 5.30$, $p < .001$, Cohen's $d = 1.11$.

Also consistent with predictions, we did not observe a BFA for guess rate. For guess rate (*g*) (Figure 2e), a significant main effect of display, $F(2, 36) = 9.86$, $p < .01$, $\eta_p^2 = .354$, was revealed by repeated measures ANOVA. Yet, there was no significant difference between the bilateral and unilateral conditions, $t(18) = 1.22$, $p = .239$, Cohen's $d = 0.15$. The single condition was significantly lower than the bilateral condition, $t(18) = 3.34$, $p < .005$, Cohen's $d = 0.96$.

Discussion

The results of Experiment 1, in line with our expectations, suggest that memory precision improved when the number of memoranda was low, since the *SD*s in the single condition were significantly lower than those in the other two conditions. More importantly, the *SD* for the bilateral condition was lower than that for unilateral displays, indicating that the BFA also conveyed enhanced precision.

To examine the parameters of the BFA precision effect more carefully, we conducted Experiment 2 to explore whether there was still a precision BFA for remembering

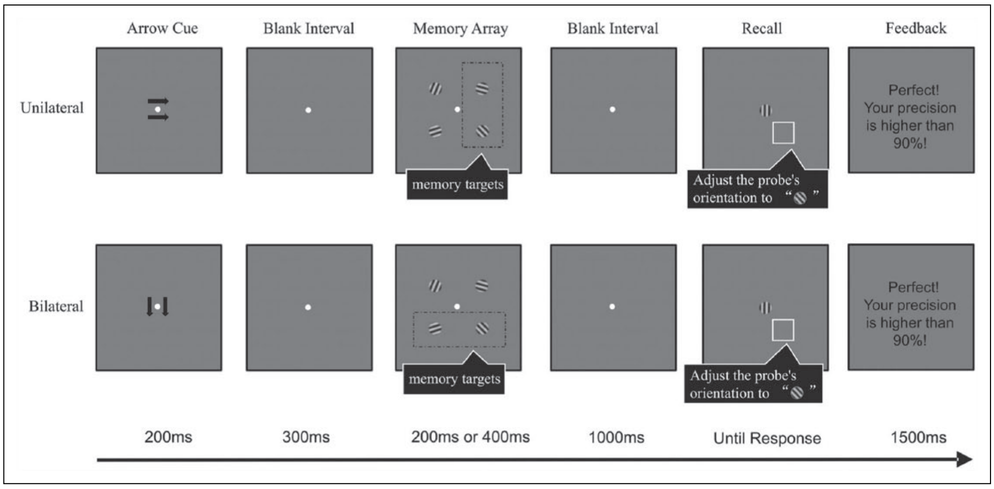

Figure 3. Schematic of Experiment 2 trial structures. Four different arrows randomly cued subjects' memory. The "right" and "left" cues make up the unilateral condition, and the "up" and "down" cues make up the bilateral condition.

two items when memory resources are challenged. Recent studies (Becker, Miller, & Liu, 2013; Liu & Becker, 2013; Gao, Ding, Yang, Liang & Shui, 2013) have indicated that orientation information is consolidated in a serial process. In that case, reduced exposure time might lead to fewer resources being allocated to each item, particularly with regard to orientation. Thus, in Experiment 2, we manipulated the exposure times (200 ms and 400 ms) within subjects to modulate the resources allocation. This manipulation allowed us to assess whether challenged resource could eliminate or reduce the BFA of precision.

Experiment 2

Method

Participants. Sixteen new volunteers (11 female), with normal colour vision and normal or corrected-to-normal visual acuity, from Liaoning Normal University, were recruited for Experiment 2. Subjects were paid ¥10 for their participation and signed written informed consent.

Procedure. The same stimuli and procedures as those used in Experiment 1 were used for Experiment 2 with the following exceptions. We removed the single condition since it was not central to testing the robustness of the BFA precision effect. We also added a within-subjects manipulation of the presentation time. This resulted in a 2 (200 ms vs. 400 ms) × 2 (bilateral vs. unilateral) experimental design. The experiment included eight blocks of 40 trials each. Subjects completed at least 20 practice trials and a total of 320 test trials (see Figure 3). The *p* values of the main effects and interactions were corrected using the Greenhouse–Geisser adjustment.

Results

We again fitted each individual's data separately with the mixture model proposed by Zhang and Luck (2008), and then averaged all participants' guessing rates and *SD*s separately across different conditions. For the precision parameter (*SD*; Figure 4a), a 2 (200 ms vs. 400 ms) × 2 (bilateral vs. unilateral) repeated measures ANOVA revealed a significant main effect of display, $F(1, 15) = 12.69$, $p < .05$, $\eta_p^2 = .458$, but no significant main effects of time, $F(1, 15) = 1.55$, $p = .231$, $\eta_p^2 = .094$. A significant two-way interaction was obtained for Time × Display, $F(1, 15) = 4.726$, $p < .05$, $\eta_p^2 = .240$. When the memory array presentation time was 200 ms, there was no significant difference between the bilateral and unilateral conditions, $t(15) = 0.387$, $p = .704$, Cohen's $d = .04$. When the memory array presentation time was 400 ms, the *SD* for the bilateral condition was significantly lower than that for the unilateral condition, $t(15) = 2.998$, $p < .01$, Cohen's $d = 0.69$. Further, when memory items were presented bilaterally, the *SD* for 400 ms was significantly lower than that for 200 ms, $t(15) = 2.194$, $p < .05$, Cohen's $d = 0.54$. When memory items were presented unilaterally, there was no significant difference between 200 ms and 400 ms, $t(15) = -0.851$, $p = .408$, Cohen's $d = 0.14$.

For guess rate (*g*; Figure 4b), there were no significant main effects of time, $F(1, 15) = 1.781$, $p = .202$, $\eta_p^2 = .106$, or display, $F(1, 15) = 0.012$, $p = .915$, $\eta_p^2 = .001$, nor a Time × Display interaction, $F(1, 15) = 1.578$, $p = .228$,

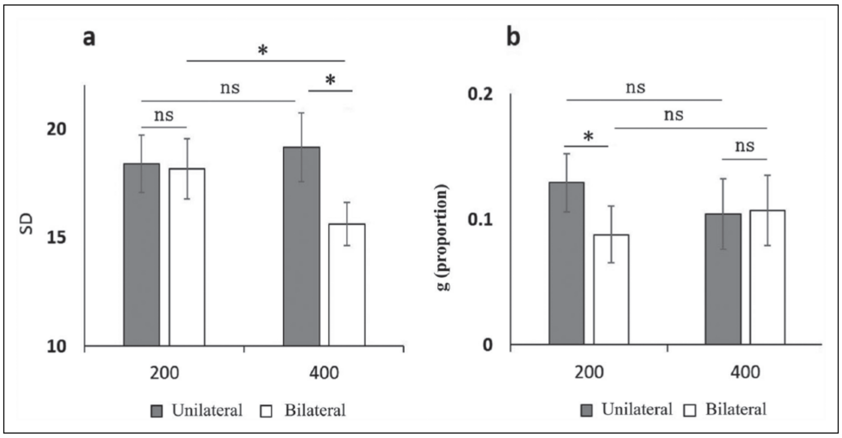

Figure 4. Model-fit results from Experiment 2. Panels (a) and (b) show *SD* and *g* as a function of condition. Error bars indicate ± 1 standard error of the mean. * Indicates a statistically significant difference between two levels of a factor; *ns* indicates no statistically significant difference between two levels of a factor.

$\eta_p^2 = .095$. We used paired *t* tests and found that there was a significant difference between the bilateral and unilateral conditions when the memory array presentation time was 200 ms, $t(15) = 2.202$, $p < .05$, Cohen's $d = 0.47$. The results of Experiment 2 were generally consistent with those from Experiment 1.

Discussion

The results of Experiment 2 at 400 ms are generally consistent with those from Experiment 1. The *SD* in the bilateral condition was still significantly lower than that in the unilateral condition, and there was no guess rate difference between the bilateral and unilateral conditions. However, inconsistent with the resource model prediction, the observed pattern of BFA in the 200 ms condition was different from that in the 400 ms condition. The *SD* differences disappeared at 200 ms, and the BFA mainly appeared in the reduction of the guess rate. The result of the 200 ms condition seems in line with the findings for four items in the study of Umemoto et al. (2010).

Alternatively, it seems to be possible that with short exposure durations, participants could be more likely to mistake which orientation was at which location during encoding. As a result, they may be more likely to report the uncued item at test. We analysed this possibility by testing the Experiment 2 data with a swap model (Bays et al., 2009); however, the incidence of mislocalization was indistinguishable between the unilateral and bilateral conditions. This indicates that mislocalization was not the influencing factor for a BFA to emerge.[1]

Though participants were told to keep their eyes focused on the fixed point throughout Experiments 1 and 2, it is still possible that they could move their eyes in the 400 ms condition (see, for example, Roberson, Hanley, & Pak, 2009). There is a possibility that the BFA in the 400 ms condition reflects a horizontal saccade advantage in VWM. The bilateral advantage observed at 400 ms exposure time might simply reflect the fact that participants have been able to move their eyes more efficiently between two bilaterally (i.e., horizontally aligned) presented items than between two unilaterally (i.e., vertically aligned) presented items. In order to test this possibility, we conducted Experiment 3.

Experiment 3

Method

Participants. Twelve new volunteers (6 female) with normal colour vision and normal or corrected-to-normal visual acuity from Liaoning Normal University were recruited for Experiment 3. Subjects were paid ¥10 for their participation and signed written informed consent.

Procedure. The same procedure as that of the Experiment 2 400 ms condition was repeated except that the invisible square (eccentricity, 3°) moved 4.24° to the left and right of the fixed point so that the two memory items were within a single hemifield (Figure 5). In the vertical condition, the two items were vertically aligned in the far left, far right, near left, or near right side of the fixed point. In the horizontal condition, the two items were horizontally aligned in the top left, top right, bottom left, or bottom right side of the fixation point. Subjects viewed the screen at a distance of 60 cm in a dim room, and they were told to

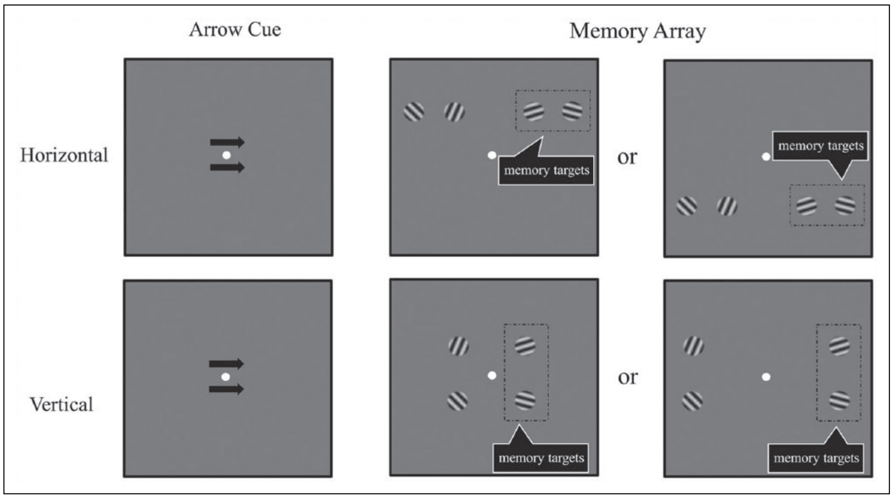

Figure 5. Schematic of Experiment 3 trial structures. Two different arrows randomly cued subjects' memory. In the vertical condition, the two items were vertically aligned in a single hemifield. In the horizontal condition, the two items were horizontally aligned in a single hemifield.

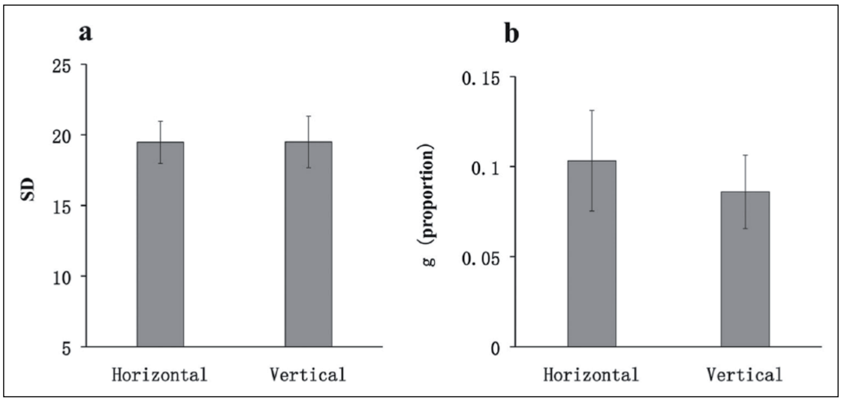

Figure 6. Model-fit results from Experiment 3. Panels (a) and (b) show *SD* and *g* as a function of condition. Error bars indicate ± 1 standard error of the mean.

keep their eyes focused on the fixed point throughout the experiment. To ensure that two memory items in both vertical and horizontal condition were in a single hemifield, there were only two possible directions for the arrows in the cue ("left" or "right"), indicating which region of the array to remember. The experiment included six blocks of 40 trials each. Subjects completed at least 30 practice trials before the test trials. The *p* values of the main effects and interactions were corrected using the Greenhouse–Geisser adjustment.

Results

Fitting the data with the mixture model proposed by Zhang and Luck (2008), we separately measured the guess rate (*g*) and precision (*SD*) of responses as a proxy for the representations that were stored in working memory, as in Experiments 1 and 2. Using paired *t* tests, we found that for the precision parameter (*SD*; Figure 6a), when the memory array presentation time was 400 ms, there was no significant difference between the horizontal and vertical conditions, $t(11) = -0.019$, $p = .985$, Cohen's $d = 0.03$. For guess rate (g; Figure 6b), the differences remained non-significant, $t(11) = 0.716$, $p = .489$, Cohen's $d = -0.20$.

Discussion

In Experiment 3, neither *SD* nor guess rate differed significantly between the horizontal and vertical conditions. Thus, the BFA of precision at 400 ms in previous experiments cannot be explained by the horizontal alignment of stimulus pairs; it must have been caused by the presentation of the two memory items in different visual hemifields.

General discussion

A large amount of previous research has demonstrated a bilateral field advantage (BFA) in visual processing (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Delvenne & Holt, 2012; Delvenne, Kaddour & Castronovo, 2011; Holt & Delvenne, 2014; Umemoto et al., 2010). In visual working memory, the bilateral distribution of information has previously been found to affect the number of items that could be maintained, but not their precision (Umemoto et al., 2010). The main purpose of the current study was to explore whether the precision of a bilateral memory array could be improved by reducing the number of memoranda. In Experiment 1, the results provided evidence that the BFA could arises in memory precision when there was sufficient time, and the number of memoranda was limited to two. The results of Experiment 2 replicated and extended Experiment 1. There was still a precision BFA at 400 ms. However, with a 200 ms presentation time, the BFA disappeared in memory precision but appeared in the guess rate. The result in the 200 ms condition provided a conceptual replication of Umemoto et al. (2010). Experiment 3 indicated that the BFA arises when the to-be-remembered items are presented in different visual hemifields rather than merely in horizontal alignment.

There are three possible explanations for a BFA in a VWM task. The first is that the BFA results from a faster rate of encoding. The second is that the representations of memory items fade away faster in the unilateral condition during the memory maintenance phase (Umemoto et al., 2010). The third is that the BFA reflects increased memory resources when items are distributed across both hemifields. An explanation based on faster encoding is unlikely, since Umemoto et al. (2010) still observed a bilateral advantage using sequentially presented stimuli, suggesting that the BFA could not be explained fully by differences in encoding speed. The second possibility is also hard to sustain, because previous studies found that the representations of memory items did not fade significantly within a retention interval of four seconds (Zhang & Luck, 2009). The memory retention time in Umemoto et al. (2010) and in the present study was only 900 ms, so forgetting is unlikely to be the cause of the BFA. Thus, the most likely explanation for the BFA in the current study is increased memory resources for visual processing in bilateral fields compared to in a single hemifield.

We discuss the result according to the main VWM models. The resource model allows for VWM resources to be flexibly allocated between items in a display, with fewer resources per item and thus reduced precision as the set size increases. Participants in Experiment 2 were asked to remember two orientations without any priority. Thus, the two orientations should have been allocated equal memory resources. According to this theory, the representational precision should differ between the bilateral and unilateral conditions, but the probability of storage should be the same for both conditions. However, the bilateral advantage in guess rate observed in 200 ms, similar to the findings from Umemoto et al. (2010), appears to be inconsistent with this theory.

Rather, this pattern of results favours an account of the BFA according to the slots + averaging model, which presumes that working memory resources are divided into discrete slots. When the memory array's set size is greater than the number of slots, more available slots lead to a decrease in the guess rate (g). When the set size of a memory array is less than the number of slots, more available slots leads to an increased precision. In that case, both the bilateral precision advantage and the bilateral guess rate advantage can be attributed to having more slots involved in memory within the bilateral condition. In addition, in Experiment 2, when memory items were presented bilaterally, the *SD* at the 400 ms presentation time was significantly lower than that for 200 ms, indicating that more slots were employed in 400 ms, which suggests that slots are sequentially employed. However, there was no difference between 200 ms and 400 ms when memory items were presented unilaterally. We consider that this may be due to a limitation in participants' working memory capacity. Most of the participants could only remember two orientations in the unilateral condition, suggesting that only two slots were available in the unilateral condition, and 200 ms presentation time is sufficient for employing two slots but is challenged for employing three slots. This suggests that no matter how long the memory array was presented in the unilateral condition, each item in the memory array could only take one slot.

However, there is no evidence that memory resources are independent in the left and right hemifields, because there is no evidence that twice as many objects can be stored in both left and right hemifields as in the same hemifield. It is more likely that left and right hemifields share the same memory resources system. Thus, the BFA seems unlikely to arise merely because bilateral fields obtain more memory resource than unilateral fields. A more likely explanation is that the total amount of memory resources would be the same in the two conditions, but the efficiency of those resources in VWM would depend on how many attentional resources can be allocated. If there are more attentional resources available in the bilateral condition, the available memory resources would be used more efficiently. As an illustrative example, imagine that there were four drawers (memory slots), powered by electricity (attentional resources). Ample electrical power might allow all four drawers to open simultaneously, but weak electrical power might allow only two drawers to open. The bilateral and unilateral conditions would both have four drawers, but the bilateral condition would have more electrical power to drive the drawers. Support for this view comes from previous studies' findings that individuals need attentional resources to maintain the VWM representation and that a strong BFA was observed in visual attention tasks (e.g., Alvarez & Cavanagh, 2005; Delvenne & Holt, 2012). It could also explain why previous BFA studies on working memory only found the effect on location and orientation rather than colour (Alvarez & Cavanagh, 2008; Ye, Zhang, Liu, Li, & Liu, 2014). The process of orientation is more likely to be tied to the involvement of visual attention. So a BFA for orientation would be more likely to arise.

In conclusion, this study shows for the first time that the BFA can be demonstrated using a precision index, and that the BFA appears to have more attentional resources available when items are spread across the two hemifields.

Note

1. The mislocalization error (b value) was quite low in every condition (mean $b < 0.024$). There was no significant difference in b value between unilateral and bilateral conditions in both 200 ms ($p = .865$) and 400 ms ($p = .137$). This indicates that mislocalization was not the influencing factor for a BFA to emerge.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by National Natural Science Foundation of China [grant number NSFC 31571123].

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VI

RETRO-DIMENSION-CUE BENEFIT IN VISUAL WORKING MEMORY

by

Chaoxiong Ye, Zhonghua Hu, Tapani Ristaniemi, Maria Gendron & Qiang Liu,
2016

Scientific Reports, 6, 35573.
Available online: http://dx.doi.org/ 10.1038/srep35573

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Retro-dimension-cue benefit in visual working memory

Chaoxiong Ye[1,2], Zhonghua Hu[1], Tapani Ristaniemi[3], Maria Gendron[4] & Qiang Liu[1,5]

Received: 24 February 2016
Accepted: 13 September 2016
Published: 24 October 2016

In visual working memory (VWM) tasks, participants' performance can be improved by a retro-object-cue. However, previous studies have not investigated whether participants' performance can also be improved by a retro-dimension-cue. Three experiments investigated this issue. We used a recall task with a retro-dimension-cue in all experiments. In Experiment 1, we found benefits from retro-dimension-cues compared to neutral cues. This retro-dimension-cue benefit is reflected in an increased probability of reporting the target, but not in the probability of reporting the non-target, as well as increased precision with which this item is remembered. Experiment 2 replicated the retro-dimension-cue benefit and showed that the length of the blank interval after the cue disappeared did not influence recall performance. Experiment 3 replicated the results of Experiment 2 with a lower memory load. Our studies provide evidence that there is a robust retro-dimension-cue benefit in VWM. Participants can use internal attention to flexibly allocate cognitive resources to a particular dimension of memory representations. The results also support the feature-based storing hypothesis.

Visual working memory (VWM) provides online storage for visual information transferred from perceptual processing; this allows people to act on visual information that is no longer present in the environment[1]. Although VWM is flexible and goal oriented, it can only represent limited information from the total sensory input. Therefore, attention must be paid to ensure that only the most relevant visual information is encoded and maintained. Based on the targets of attention, attention can be classified as external attention and internal attention[2]. The former refers to the selection and modulation of sensory information, and the latter refers to the selection, modulation, and maintenance of internally generated information. In recent years, a number of studies have examined the influence of internal attention on VWM.

Griffin and Nobre[3] investigated whether it is possible to orient selective spatial attention to internal representations held in VWM. They used a change detection task, which asked participants to remember four colors. Some participants received a retro-cue, which oriented them to a spatial location in working memory after the stimulus array disappeared. They found that, compared to a non-cue condition, there was a stable benefit in task performance from the presence of a retro-cue (also see Landman, *et al.*[4]). These results suggest that, even when the visual stimulus and iconic memory are gone, directing internal attention can still influence VWM representations.

Researchers put forward a variety of explanations of the mechanisms of the retro-cue benefit. Some researchers suggested that the performance for a cued item is improved due to an enhancement or strengthening of the representation of the cued item. As a result, the cued item suffers from less competition from the non-cued items in VWM, and this leads to faster and more accurate retrieval of the cued item. According to this assumption, non-cued items are maintained in VWM unchanged, but they are less accessible than the cued item[5–9]. Other researchers suggested that retro-cue can help to reduce memory load by removing non-cued items from VWM, thus the participant would have more free VWM resources to maintain the cued item[9–11]. Another suggestion is that attention is oriented to a particular memorized item, which makes VWM more resistant to visual interference from the test probe[12–15]. In addition, there are a series of studies suggesting a third memory stage, termed fragile visual short-term memory (FM), seems to exist between the iconic memory and robust VWM. FM has a large capacity (at least 2 items more than VWM) and long-lasting lifetime, it can exist almost as long as VWM without interference of new stimulation input. Thus, another account of the retro-cue benefit is that it arises

[1]Research Center of Brain and Cognitive Neuroscience, Liaoning Normal University, Dalian, 116029, China. [2]Department of Computer Science and Information Systems, University of Jyväskylä, Jyväskylä, 40014, Finland. [3]Department of Mathematical Information Technology, University of Jyväskylä, Jyväskylä, 40014, Finland. [4]Interdisciplinary Affective Science Laboratory, Northeastern University, Boston, MA, 02115, USA. [5]Key Laboratory for NeuroInformation of Ministry of Education, University of Electronic Science and Technology of China, Chengdu, 610054, China. Correspondence and requests for materials should be addressed to Q.L. (email: lq780614@163.com)

because the participants selectively transfer the cued item from FM to robust VWM[4,16–19]. Finally, other researchers suggested that memory representations become degraded during the retention interval, and participants can use attention to protect the cued item from this degradation, or refresh the cued item to improve retrieval[20–23]. Of course, these explanations of the retro-cue benefit may not be mutually exclusive. For instance, strengthening and removal are not necessarily incompatible processes. It is possible that a cued item is strengthened and non-cued items are removed at the same time[9,24].

To our knowledge, in previous studies using the retro-cue task, three main types of retro-cues were used. The first type of retro-cue is endogenous cue, which is presented at the center of the screen and points to a target location[3,4,7–9,11,13,15,17–20,22,25–46]; the second type of retro-cue is exogenous cue, presented in the target location[9,12,19,29,31,43,47–49]; the third type of retro-cue is feature cue, which is presented at the center of the screen and cues participants to one feature of the previously presented items. For example, participants receive a red color cue, and then should direct attention to the shape of the red colored memory representation[33,43–45,50,51]. By using these three types of cues, participants can direct internal attention to a single representation in VWM, so that the allocation of attention resources can be managed to obtain a retro-cue benefit. We termed these three type of cues as the retro-object-cues. Thus, previous explanations of the retro-cue benefit were developed to account for how a retro-object-cue can improve VWM performance.

However, beyond selecting information in an object-based manner, attention can also be deployed in a dimension-based manner. For example, researchers have studied the impact of cuing attention to a dimension in an external attention task (i.e., in visual search). Müller, *et al.*[52] found that a valid semantic pre cue of a dimension of upcoming targets could be used to improve the performance in a search task. Previous researchers proposed a dimension-weighting account to explain how participants could use external attention to select a particular dimension from visual information input to improve search performance[53,54]. The dimension-weighting account assumes that the pop-out is ultimately based on the saliency activity integrated across separate dimensional saliency maps. As the total amount of weight is limited, an increase of weight assigned to one dimensional map entails a reduction of the weight assigned to other dimensional maps. If the target dimension is known in advance, the saliency signals from the target dimension are amplified relative to signals from other dimensions, which could help to guide the allocation of external attention. In addition, recent research also investigated the impact of selecting a dimension of external attention on VWM encoding. They asked participants to remember one dimension of all objects, while ignoring other dimensions and found that a change of stored task-irrelevant dimension dramatically affects performance, which suggested that VWM encoding is an object-based process. That is, whenever participants use external attention to select one dimension into VWM, the other dimensions are also memorized automatically[55].

To recap, prior studies of internal attention and VWM mainly investigated that the influence of object-based cuing on VWM representations. Whereas previous studies that employed dimension-based cuing mainly focused on selection in external attention tasks. To our knowledge, there are no studies exploring the influence of dimension-based cuing on internal attention to VWM representations[24]. This is critical since the impact of dimension-based internal attention may depend on a completely different mechanism than object-based internal attention. Thus, in the present study we offered participants a retro-dimension-cue in a VWM task to observe if there is a retro-dimension-cue benefit and to further explore its potential mechanism.

In addition, the present study can also address another basic issue in the VWM literature. That is, what is the format of memory representations[56]? Two hypotheses have been proposed. The object-based storing hypothesis suggests that a given VWM representation is structured as a set of monolithic object representations, such that additional feature information will be maintained "for free" after all features have been integrated into one memory unit[57,58]. The other hypothesis, called the feature-based storing hypothesis, suggests that the visual features such as colors and orientations are independent and stored separately from each other, such that objects have multiple feature levels of representation in VWM[59]. These hypotheses would predict different result patterns for the effect of a retro-dimension-cue on a VWM task. Based on the object-based storing hypothesis, because features are bound to an integrated object, participants cannot forget a task-irrelevant feature of an integrated object, or weight resources to a task-relevant features of an integrated object. As a result, an object-based storing hypothesis might expect that the retro-dimension-cue would not result in a benefit. However, based on the feature-based storing hypothesis, because different features are stored separately, participants can use the retro-dimension-cue to reduce memory load by forgetting task-irrelevant features or enhance the memory of task-relevant features. As a result, according to a feature-based storing hypothesis we might expect better performance when we present a valid retro-dimension-cue to participants. In some sense, the predicted effect from this view is similar to a previous study, which presented two encoding displays and participants are told which display is going to be tested and which can be dropped[60]. Therefore, the results of the present experiments testing for a retro-dimension-cue can weigh in on the debate between the object-based storing hypothesis and the feature-based storing hypothesis.

In the present study, we used a recall task which included a retro-dimension-cue condition. One advantage of using a recall task is that it allows us to use model fitting, with the swap model[61], to separate the mnemonic parameters of guess rate, non-target reported rate and memory precision. If there is a retro-dimension-cue benefit, the improvement of behavioral performance may result from multiple sources: an increase in memory precision, a decline in non-target reported rate, or a decline in the guess rate. Therefore, we unpacked the potential sources of the retro-dimension-cue benefit by using the swap model in our recall task. Another advantage of the recall task is that it could help to minimize interference produced by presenting a probe stimulus in the location of the memory object[10,62].

Experiment 1

Methods. We asked participants to perform a double dimension recall task, in which 50% of the trials contained a valid cue, and the remainder 50% of trials contained a neutral cue. We also used the swap model to

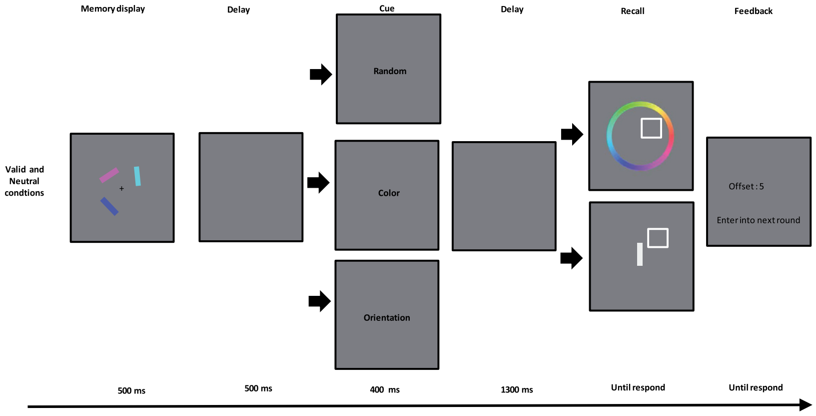

Figure 1. Trial structure of Experiment 1. In the neutral condition, the retro-cue was "Random" (top line); in the valid condition, the retro-cue was "Color" or "Orientation" (middle and bottom lines).

calculate the probability of guessing, non-target reporting and memory precision in each condition. This allowed us to observe whether a benefit of the retro-dimension-cue existed by comparing these two conditions.

Participants. Twenty undergraduate students (18 females, 18–21 years old) were recruited from the participant pool at the Minnan Normal University and received course credit for their participation. All participants had normal or corrected-to-normal vision and no history of neurological problems. Written informed consent was provided by each participant prior to the experiment. The study conformed to the Declaration of Helsinki and was approved by the ethics committee of Liaoning Normal University.

Stimuli. Visual stimuli were generated colored bars (1.1° in length, 0.4° in height) presented on a gray background. The color and orientation of each memory stimulus were randomly selected from 360 possible colors (1–360, in 1 color step) and 180 possible angles (1–180, in 1 step). A palette of 360 colors was used. The RGB values were assigned to ensure all the presented colors were highly saturated. The RGB value n was assigned the value as follows:

$$[255, 75 + 3 \times n, 75] \text{ for } 0 <= \text{n} <= 59$$

$$[255 - 3 \times (n - 60), 255, 75] \text{ for } 60 <= \text{n} <= 119$$

$$[75, 255, 75 + 3 \times (n - 120)] \text{ for } 120 <= \text{n} <= 179$$

$$[75, 255 - 3 \times (n - 180), 255] \text{ for } 180 <= \text{n} <= 239$$

$$[75 + 3 \times (n - 240), 75, 255] \text{ for } 240 <= \text{n} <= 299$$

$$[255, 75, 255 - 3 \times (n - 300)] \text{ for } 300 <= \text{n} <= 359$$

The bars could be presented in four possible locations, located at the corners of an imaginary square (eccentricity, 3°), with any two bars separated by at least 30 orientation degrees and 60 color steps. A fixation cross (0.2°) was presented in the center of the screen before the memory display onset. The valid cue stimuli were word "Color" ("*颜色*", in Chinese), "Orientation" ("*方向*", in Chinese) or neutral cue word "Random" ("*随机*", in Chinese) presented in black simsun-normal font (approximately 3.2° × 1.5°) at the center of the screen. The probe display of the color recall task consisted of an outlined square and a color wheel (5.8° inner radius; 2.2° thickness). The probe display of the orientation recall task consisted of an outlined square (1.2° × 1.2°) and a vertical white bar (1.1° × 0.4°, presented at fixation). The stimuli were presented on a 19" LCD monitor (1280 × 1024 pixel), and participants viewed the display at a distance of 60 cm in a dark room.

Task and design. Participants were asked to perform double dimension recall tasks with the trial structures depicted in Fig. 1. Retro-dimension-cue type (valid, neutral) and report type (color, orientation) were manipulated within participants. Half of the trials included a retro-dimension-cue during the retention interval and these were randomly interleaved with the trials that included a neutral cue. All trials began with a fixation cross for 300 ms in the center of the screen. A memory display containing three colored bars was then presented for 500 ms.

Participants were instructed to memorize both the color and orientation of the bars. After 500 ms had elapsed from the offset of the memory display, a dimension-cue ("Color" or "Orientation", 100% valid) was presented at the center for a duration of 400 ms in the valid trials, and a neutral cue ("Random") appeared for a duration of 400 ms in the neutral trials. The cue was then followed by the rest of the retention interval, which lasted 1300 ms. After the retention period, participants were asked to report on the color or orientation. The report type was selected at random on each trial. A white square outline appeared at the location of the probed VWM stimulus. For color report trials, a response wheel with invisible boundaries was centered on the fixation and consisted of 360 colored segments corresponding to possible stimulus colors. Participants were asked to report the color of the stored item at the location of white square outline. Participants selected one of 360 color values by clicking the left mouse button when the cursor was located in the desired value of the wheel. For orientation report trials, an adjustable vertical white bar was presented at fixation. Participants adjusted the white bar's orientation to match that of the cued bar. Participants moved the cursor with the mouse; they pressed the left mouse button to rotate the white bar to the cursor position, and pressed the right mouse button to finalize their response when they were satisfied. Responses were not under time constraints. After the probe display disappeared, feedback on response error (in degrees) was provided. The next trial started 900–1100 ms after the feedback.

There were 100 trials for each condition (valid-color, neutral-color, valid-orientation, neutral-orientation), with a total of 400 trials. Trials were fully randomized. The task was split into 4 mini-blocks of 100 trials each, with a break of at least 15 s between mini-blocks. The entire experiment lasted approximately 60 min. Instructions at the beginning of each block informed participants of the task, and participants completed at least 16 practice trials before the main task.

Data Analysis. We computed the errors for each participant and each experimental condition (valid-color, neutral-color, valid-orientation, neutral-orientation) by subtracting the probed item's value from the response. The main dependent variable was the absolute value of the deviation, which we called it offset. Then, we calculated a retro-dimension-cue benefit index (RDBI), which was defined as

$$RDBI = \frac{Offset\,(neutral) - Offset\,(valid)}{Offset\,(neutral)}$$

RDBI was thus the relative improvement between the valid and neutral conditions.

For each trial, we also calculated the errors in the reported color (or orientation) by subtracting the participant's color (or orientation) setting from the memory color (or orientation). For model fitting, we fit the error data with the swap model using the MemToolbox[63]. This model assumes that participant's behavior results from a mixture of three types of trials: On the first proportion of trials, participants hypothetically consolidated the items into VWM, which contains a noisy representation of the target color (or orientation), conformed to a von Mises distribution. On the second proportion of trials, participants hypothetically did not consolidate the items into VWM and simply guessed the reported color (or orientation) randomly, which should produce a uniform distribution. On the third proportion of trials, participants hypothetically reported the non-target color (or orientation) during the response phase, which is distribution of responses around non-target. For example, participants might report a non-target orientation on an orientation report trial or report a non-target color on a color report trial. This allowed us to estimate the guess rate (P_g), the precision of the memory representation (SD) and non-target reported rate (P_b) respectively. We fit the swap model to individual participant data in each condition.

Results. The offsets were lower in the valid condition than in the neutral condition for both color report trials, $t(19) = 5.402$, $p < 0.001$, Cohen's $d = 2.48$, and orientation report trials, $t(19) = 6.017$, $p < 0.001$, Cohen's $d = 2.76$ (Fig. 2). The mean RDBI was 17.5% for color and 16.2% for orientation, which were both significantly greater than zero, $t(19) = 6.258$, $p < 0.001$, Cohen's $d = 2.87$ (color), $t(19) = 7.484$,$p < 0.001$, Cohen's $d = 3.73$ (orientation). The results demonstrate that the appearance of the retro-dimension-cue can lead to better performance.

For the precision parameter (SD), there was no significant difference between the valid condition and the neutral condition for both color report trials, $t(19) = 0.248$, $p = 0.807$, Cohen's $d = 0.11$, and orientation report trials, $t(19) = 1.261$, $p = 0.223$, Cohen's $d = 0.58$. The Bayes factor analysis showed that the null hypothesis (i.e., no difference between the valid and neutral conditions) was 4.186 times (for reporting color) and 2.155 times (for reporting orientation) more likely to be true than the alternative hypothesis (a difference between conditions). For the non-target reported rate (P_b), there was also no significant difference between the valid condition and neutral condition for both color report trials, $t(19) = 1.131$, $p = 0.272$, Cohen's $d = 0.52$, and orientation report trials, $t(19) = 1.244$, $p = 0.229$, Cohen's $d = 0.58$. The Bayes factor analysis showed that the null hypothesis was 2.457 times (for reporting color) and 2.194 times (for reporting orientation) more likely to be true than the alternative hypothesis. In contrast, the guess rates (P_g) were significantly lower in the valid condition than in neutral condition, for both color report trials, $t(19) = 2.206$, $p = 0.040$, Cohen's $d = 1.01$, and orientation report trials, $t(19) = 2.383$, $p = 0.028$, Cohen's $d = 1.09$ (Fig. 3). In sum, the results showed that the appearance of the retro-dimension-cue led to a lower guess rate, but did not influence the non-target reported rate and memory precision.

Discussion. We asked participants to remember three colored bars, and found that a retro-dimension-cue could improve recall performance, indicating that there is a retro-dimension-cue benefit. In addition, we found that the source of the retro-dimension-cue benefit was not an increase in memory precision or a decline in non-target reported rate, but instead due to a decline in the guess rate. These results demonstrate that participants could use internal attention to select a dimension as target to improve the VWM representation of task-relevant dimension. However, as the object-based storing hypothesis would predict that the retro-dimension-cue could not cause a benefit of performance, these results do not provide evidence consistent with the object-based storing hypothesis of VWM.

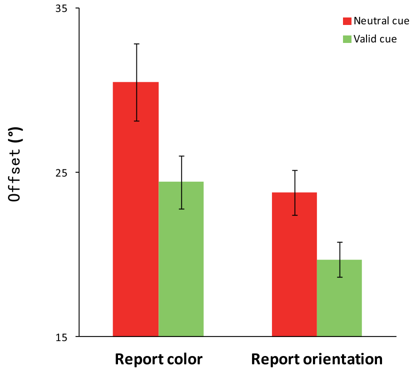

Figure 2. The offset results of Experiment 1. Error bars are standard errors of the mean.

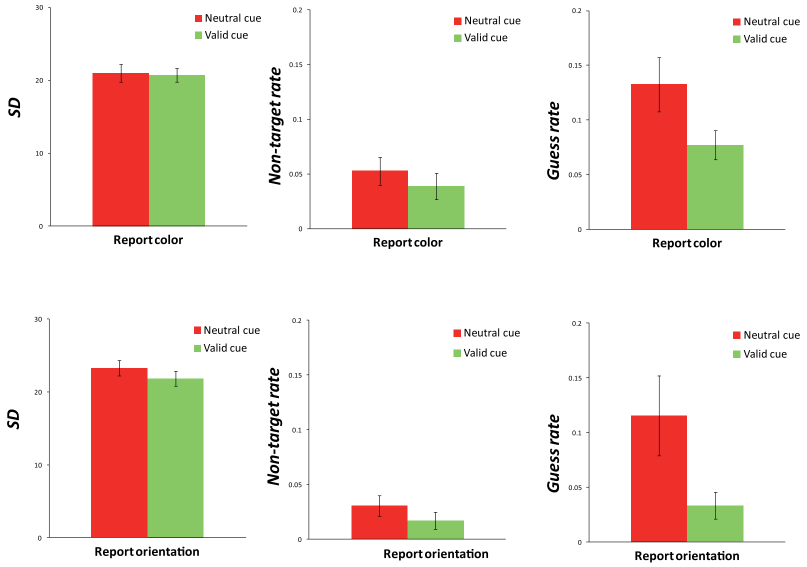

Figure 3. The results of Experiment 1 for memory precision (SD), non-target reported rate (P_b), and guess rate (P_g). The results of the report color (top line) and report orientation (bottom line) conditions are illustrated. Error bars are standard errors of the mean.

One innovation of the present study was that we used a dimensional semantic word cue in a retro-cue task. Using cue words is a typical approach when researchers investigate whether knowledge of a dimension of an upcoming target will influence attention. For example, Müller, *et al.*[52] investigated the issue by presenting a symbolic cue, the word "color", "orientation" or "neutral", to participants before a pop-out search task. Their results demonstrated that participants could use top-down control to bias their attentional weight to a task-relevant dimension based on the cue word. Further, there are a few retro-cue effect studies which presented a symbolic cue word as the retro-object-cue. Such as, the word "red ", "circle" or "wait" in Gilchrist, *et al.*'s[50] study, and the word "red", "green" or "all" in Hollingworth and Maxcey-Richard's[33] study. Our results showed that dimensional cue words can elicit a retro-dimension-cue benefit, consistent with prior work demonstrating that a semantic word cue is effective. Further, using semantic cue words provided an additional source of experimental control since it minimized the visual difference between valid and neutral cues (i.e., both were words).

One prior study has questioned whether object-based feature-cues are able to elicit a benefit. Berryhill, *et al.*[43] found that a top-down retro-cue (a digit that mapped onto the location of one item) failed to evoke a retro-cue benefit. However, other research has demonstrated that object-based feature-cues can cause a retro-cue benefit[45]. In the present study, we also found that dimension-cues as a top-down retro-cue can benefit performance. One critical difference between Berryhill, *et al.*'s[43] study and our own is the retention interval. The cue of our study was followed by a rest period of a 1300 ms (a retention interval) before the response period, whereas there was only a 400 ms retention interval between the cue and response in Berryhill, *et al.*'s[43] study. Thus, it may take more time to use a retro-feature-cue to elicit a benefit. Even a spatial cue may require more than 400 ms to be effective, a recent study of van Moorselaar, *et al.*[39] suggested that it takes about 500 to 600 ms to completely use an arrow cue to protect against perceptual interference. This could explain why we observed a benefit of retro-cue in our study, but no such benefit was observed in Berryhill, *et al.*'s[43] study.

We also want to note that, importantly, in contrast to object-based feature-cues, dimension-based cues are abstract entities: In general feature-cues are used to describe target such as "the orientation of the *red* bar," whereas statements such as "the orientation of a *colored* bar" used in dimension-cues do not convey any useful information to select one object. As a result, we need to be cautious about drawing conclusions from a dimension manipulation to other types of retro-cues, or from other types manipulation to retro-dimension-cues. There may be different mechanisms at play in feature-cue and dimension-cue experiments. As the retro-dimension-cue benefit is a new finding, Experiment 2 was conducted to try to replicate the results and further explore the mechanisms of retro-dimension-cue benefit.

Experiment 2

There were two purposes in Experiment 2. The first purpose was to replicate the retro-dimension-cue benefit observed in Experiment 1. More importantly, the second purpose was to test whether the retro-dimension-cue benefit results from protection of representations of the cued dimension from degradation over time[20,21]. In other words, during maintenance, representations of the cued dimension might be unaffected by temporal decay that typically degrades representations of non-cued dimensions. The procedures of Experiment 2 were similar to those in Experiment 1, with the exception that we added short-delay neutral conditions to compare with the normal-delay neutral conditions. In the normal-delay neutral condition, the probe display appeared 1300 ms after the neutral cue ("Random") disappeared. In the short-delay neutral condition, the probe display appeared only 50 ms after the neutral cue ("Random") disappeared. This manipulation allows us to test whether there is a degradation effect in the VWM task. If there is a degradation effect, VWM performance will be better in the short-delay neutral condition than in the normal-delay neutral condition. On the contrary, if there is no difference of VWM performance between the normal-delay neutral and short-delay neutral conditions, this would demonstrate that there is no degradation effect in our experimental task. This would effectively rule out protection from degradation as a potential mechanism underlying the retro-dimension-cue benefit in our experimental task.

Methods. *Participants.* Twenty-eight undergraduate students (26 females, 19–22 years old) were recruited from the participant pool at the Minnan Normal University and received course credit for their participation. All participants had normal or corrected-to-normal vision and no history of neurological problems. Written informed consent was provided by each participant prior to the experiment. The study conformed to the Declaration of Helsinki and was approved by the ethics committee of Liaoning Normal University.

Task and design. The design and procedure of Experiment 2 were identical to those of Experiment 1, except for the following changes: 1) Addition of two short-delay neutral conditions (one condition for color report, the other for orientation report). The procedure of short-delay neutral conditions in Experiment 2 was similar to neutral conditions in Experiment 1, except that the duration of the ISI between the neutral cue and the probe display was reduced from 1300 ms to 50 ms; 2) Adjusted number of trials. The number of trials in each condition (valid-color; short-delay neutral-color; neutral-color; valid-orientation; short-delay neutral-orientation; neutral-orientation) was reduced to 50. Thus, there was a total of 300 trials, which were fully randomized. The task was split into 3 mini-blocks of 100 trials each, with a break of at least 15 s between mini-blocks. The trial structures are depicted in Fig. 4. The entire experiment lasted approximately 50 min. Instructions at the beginning of each block informed participants of the task, and participants completed at least 16 practice trials before the main task.

Results. For the offsets, one-way ANOVAs with cue condition as a factor (valid, short-delay neutral, normal-delay neutral) yielded a main effect for both color report trials, $F(2,54) = 32.030$, $p < 0.001$, $\eta^2 = 0.54$, and orientation report trials, $F(2,54) = 11.201$, $p < 0.001$, $\eta^2 = 0.29$. Post-hoc comparisons showed no significant difference in offsets between short-delay neutral and normal-delay neutral conditions for both color report trials, $t(27) = 1.628$, $p = 0.115$, Cohen's $d = 0.63$, and orientation report trials, $t(27) = 1.328$, $p = 0.195$, Cohen's $d = 0.51$. The Bayes factor analysis showed that the null hypothesis was 1.548 times (for reporting color) and 2.261 times (for reporting orientation) more likely to be true than the alternative hypothesis. The offsets were significantly lower in the valid condition than in the normal-delay neutral and short-delay neutral conditions for both color report trials, $t(27) = 5.410$, $p < 0.001$, Cohen's $d = 2.08$ (normal-delay neutral vs. valid), $t(27) = 7.188$, $p < 0.001$, Cohen's $d = 2.77$ (short-delay neutral vs. valid) and orientation report trials, $t(27) = 4.482$, $p < 0.001$, Cohen's $d = 1.73$ (normal-delay neutral vs. valid), $t(27) = 3.478$, $p = 0.002$, Cohen's $d = 1.34$ (short-delay neutral

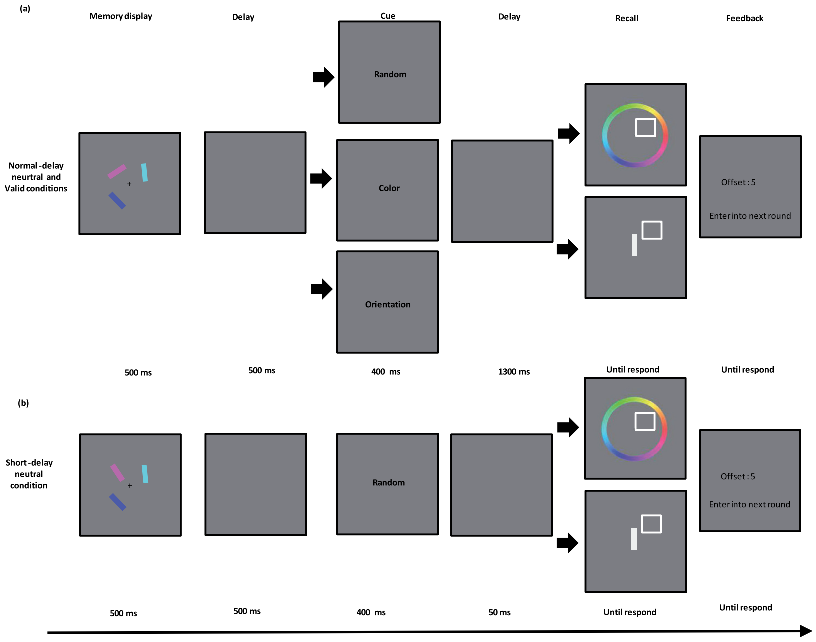

Figure 4. Trial structure of Experiment 2. (**a**) The normal-delay neutral and valid condition are illustrated. (**b**) The short-delay neutral condition is illustrated.

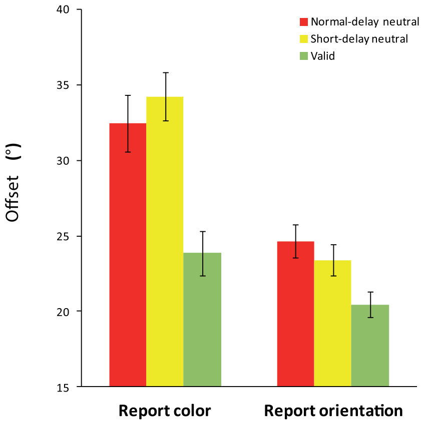

Figure 5. The offset results of Experiment 2. Error bars are standard errors of the mean.

vs. valid) (Fig. 5). The results showed that the length of delay did not influence recall performance, and that the retro-dimension-cue led to better performance compared to both neutral conditions.

The mean RDBI was 23.6% for color and 15.1% for orientation, and both were significantly greater than zero, $t(27) = 5.095$, $p < 0.001$, Cohen's $d = 1.96$ (color), $t(27) = 4.680$, $p < 0.001$, Cohen's $d = 1.80$ (orientation). These results demonstrate a retro-dimension-cue benefit in Experiment 2.

Discussion. Experiment 2 replicated the observed benefit of a retro-dimension-cue. The experiment further suggested that after the disappearance of the neutral cue, the length of the blank interval did not influence recall performance. This finding indicates that memory representations did not become degraded during the retention interval in our task. Since we did not observe memory degradation due to the blank interval, the retro-dimension-cue benefit should not be simply interpreted as a protective mechanism against memory degradation.

Experiment 3

Vogel and Awh[64] used a change detection task to test 170 undergraduate students' VWM capacity, and determined that the average memory capacity was 2.9. Thus, the memory set size of 3 in Experiment 1 and 2 could be considered a high VWM load set size for some participants. Lavie, *et al.*[65] suggested an active mechanism of attentional control is needed for rejecting non-target information. But the capacity to engage in active control is expected to be weakened under high VWM load, resulting in increased processing of non-target information during the response phase. Consistent, our previous EEG study found that a non-reported dimension is computed automatically at a neural level before the response judgment[66], such that computed outputs might interfere the response phase and negatively impact performance. Thus, when the memory load is potentially exceeding average capacity (i.e., Experiments 1 and 2), participants might suffer interference from processing of a non-reported dimension in the neutral condition, and the retro-dimension-cue can be used to reduce this interference by suppressing or removing non-reported dimension information in advance. If this is the only mechanism of retro-dimension-cue benefit, then when the memory load is lower, capacity available for rejecting information of non-reported dimension should be strengthened even in the neutral condition. This would lead to corresponding reduction of the retro-dimension-cue benefit. Thus we performed Experiment 3 with a reduced set size of items (down from three to two), and tested whether the retro-dimension-cue benefit disappeared when the set size was lower. If the benefit remained, we planned to further compare the RDBI of Experiment's 2 and 3 to observe whether the degree of retro-dimension-cue benefit is impacted by the reduction of set size. We also reserved the short-delay neutral conditions, as in Experiment 2, to replicate the lack of degradation effect at low VWM load.

Methods. *Participants.* Twenty-four undergraduate students (17 females, 18–21 years old) were recruited from the participant pool at the Minnan Normal University and received course credit for their participation. All participants had normal or corrected-to-normal vision and no history of neurological problems. Written informed consent was provided by each participant prior to the experiment. The study conformed to the Declaration of Helsinki and was approved by the ethics committee of Liaoning Normal University.

Task and design. The design and procedure of Experiment 3 were identical to those of Experiment 2, except that the total number of items in the memory display was reduced to two. On each trial, two colored bars were presented in two randomly chosen locations out of the four possible locations.

Results. For offsets, one-way ANOVAs with cue condition as a factor (valid, short-delay neutral, normal-delay neutral) yielded a main effect for both color report trials, $F(2,46) = 8.548$, $p < 0.001$, $\eta^2 = 0.27$, and orientation report trials, $F(2,46) = 20.189$, $p < 0.001$, $\eta^2 = 0.54$. Post-hoc comparisons showed no significant difference in offsets between the short-delay neutral condition and the normal-delay neutral condition for both color report trials, $t(23) = 0.028$, $p = 0.978$, Cohen's $d = 0.01$, and orientation report trials, $t(23) = 0.991$, $p = 0.332$, Cohen's $d = 0.41$. The Bayes factor analysis showed that the null hypothesis was 4.657 times (for reporting color) and 2.998 times (for reporting orientation) more likely to be true than the alternative hypothesis. The offsets were significantly smaller in the valid condition than in the normal-delay neutral and short-delay neutral conditions for both color report trials, $t(23) = 3.312$, $p = 0.003$, Cohen's $d = 1.38$ (normal-delay neutral vs. valid), $t(23) = 3.556$, $p = 0.\ 0.002$, Cohen's $d = 1.48$ (short-delay neutral vs. valid) and orientation report trials, $t(23) = 4.589$, $p < 0.001$, Cohen's $d = 1.91$, (normal-delay neutral vs. valid), $t(23) = 5.438$, $p < 0.001$, Cohen's $d = 2.27$ (short-delay neutral vs. valid) (Fig. 6). These results showed that the retro-dimension-cue benefit is observed when the memory load is low.

The mean RDBI was 16.5% for color and 16% for orientation, both were significantly higher than zero, $t(23) = 2.686$, $p = 0.013$, Cohen's $d = 1.12$ (color), $t(23) = 4.083$, $p < 0.001$ (orientation), Cohen's $d = 1.70$. In addition, we conducted a one-way ANOVA on the RDBI by treating the experiment as between-subject factor (Experiment 2 vs. Experiment 3). We found that the main effect of experiment was not significant for both color report trials, $F(1,50) = 0.881$, $p = 0.352$, $\eta^2 = 0.02$, and orientation report trials, $F(1,50) = 0.27$, $p = 0.87$, $\eta^2 = 0.00$. The results showed that the degree of retro-dimension-cue benefit in Experiment 3 was similar to the results of Experiment 2, such that no significant decrease in the retro-dimension-cue benefit was observed with the reduction of set size.

Discussion. In addition to replicating the null effect of retention interval, ruling out a degradation protection mechanism in our paradigm, the results of Experiment 3 showed that the retro-dimension-cue benefit was robust at a low VWM load, such that no reduction of the retro-dimension-cue benefit was observed compared to Experiment 2. These results demonstrated that the mechanism of the retro-dimension-cue benefit could not be simply be attributed to using the retro-cue to reduce interference from processing of a non-reported dimension during the response phase.

General discussion

In Experiment 1, we found that performance was significantly better in the valid condition than in the neutral condition, and that the guess rate was significant lower in the valid conditions than in neutral condition, but there

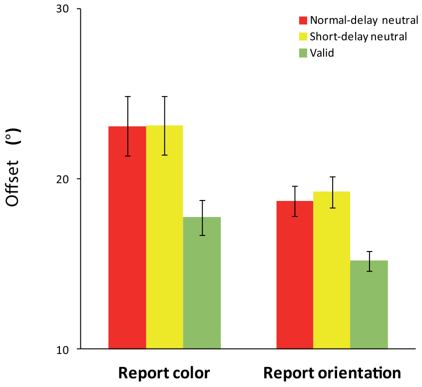

Figure 6. The offset results of Experiment 3. Error bars are standard errors of the mean.

was no significant difference for non-target reported rate and memory precision between the valid and neutral conditions; in Experiments 2 and 3, when the set size was three and two, respectively, we found that there was no significant difference for behavior performance between the short-delay neutral and normal-delay neutral conditions, and performance was better in the valid condition than in both neutral conditions. Further, in these experiments, we found the same stable pattern of results regardless of whether participants were asked to report on color or orientation. Taken together, these findings indicate that participants can use a retro-dimension-cue to improve behavioral performance regarding a specified dimension during the maintenance process.

Which mnemonic parameter is affected by the retro- dimension-cue? In Experiment 1, we found that there was no difference in memory precision across conditions, but a lower guess rate in the valid condition than neutral condition. The swap model results showed that the improvement in performance as a function of retro-dimension-cue is reflected in an increased probability of reporting the target, but not on the probability of reporting the non-target and precision with which this item is remembered.

To our knowledge, this is the first study to use a recall task with a retro-dimension-cue. Previous studies showed that there is an inverse relationship between VWM number and memory precision[61,67], so it follows that participants could use a spatial retro-cue to improve memory precision by removing the non-target representations. This is also confirmed by previous findings that a retro-object-cue benefit served to decline the guess rate and enhance the memory precision at the same time[10,12,39]. However, in our paradigm, participants could not use the retro-dimension-cue to decrease the number of items in VWM. Thus the mechanisms of a retro-object-cue may be completely different from the mechanisms of a retro-dimension-cue. Therefore, although we did not find the retro-dimension-cue improved memory precision, this finding is not conflict with the previous research demonstrating that retro-object-cues enhance memory precision.

Our findings may also appear to stand in contrast to Fougnie, *et al.*[68]. Fougnie, *et al.*[68] used a recall task and asked participants to remember double dimension and single dimension representations, and found that there was no significant difference for guess rate between the double and single dimension condition, but the memory precision was higher in the single dimension condition than double dimension condition. We suggest that the different pattern of results between Fougnie, *et al.*'s[68] study and our study is expected, because in Fougnie, *et al.*'s[68] study, the task requirements were different between the double and single dimension conditions. As a result, participants were likely already processing the two conditions differently during the VWM consolidation phase. However, in our study, participants needed to remember both dimensions of memory items on each trial and the valid trials and neutral trials were randomly mixed. In each trial before the cue appeared, participants could not know if they will see a neutral cue or a valid cue, also could not know if they will be asked to report a color dimension or an orientation dimension. This experimental design might encourage participants to encode dimensions separately by only asking them to report a single dimension in each trial, but regardless of the encoding strategy, the cognitive processes before the cue appeared would be similar in the valid and neutral conditions.

Finally, a change in guess rate in our experiment, rather than precision, would be expected based on Bays, *et al.*[67]. Critically, Bays, *et al.*'s[67] study demonstrates that a change in the precision of VWM representations occurs mainly in the early phase of encoding (i.e., the VWM consolidation phase) but not the VWM maintenance phase. Improving memory precision requires the perceiver to acquire new information from the visual stimulus, such that once the stimulus disappears, participants cannot enhance memory precision of representations any more. In our study, when the retro-dimension-cue appeared, the visual stimulus had already disappeared. Thus, participants did not have access to new visual information to improve memory precision. Therefore, the benefit of retro-dimension-cue is reflected in the stability of VWM representation, as demonstrated in the lower guess rates we observed.

The mechanism of retro-dimension-cue benefit. We found that there were no performance differences between the short-delay neutral and normal-delay neutral conditions in Experiments 2 and 3. These results suggested that the length of the blank interval after cue disappearing did not influence recall performance. The lack of degradation effect is inconsistent with Pertzov, *et al.*'s[21] study, which found a degradation effect in the retro-cue task. We think there are at least two reasons for this difference. First, Pertzov, *et al.*[21] asked participants to remember four colored bars, but participants only need to remember two to three colored bars in our study. As Pertzov, *et al.*[21] pointed out in their article, "multiple memory items may compete for memory resources and suppress each other's representation leading to memory degradation". Since we included fewer memory items, this should lead to less loss across time making it unlikely to observe a degradation effect in our Experiments 2 and 3. The second reason is that, In Pertzov, *et al.*'s[21] study, behavioral performance was only slightly decreased from the 100 ms to the 1000 ms interval condition after the cue disappeared, but was significantly decreased from the 1000 ms to 3000 ms interval (for 100 ms interval, mean of errors is 11.8, SEM is 0.9; for 1000 ms interval, mean of errors is 13.9, SEM is 1.0; for 3000 ms interval, mean of errors is 18.4, SEM is 1.1). This is consistent with Zhang and Luck's[69] study which suggests that memory representations are not degraded during short intervals, but are suddenly degraded following long intervals. In our study, we use a 50 ms interval after the neutral cue disappeared as the short interval condition and 1300 ms interval as the long interval condition. Thus, even the longer interval condition is likely insufficient to elicit a degradation effect for remembering three colored bars. This reasoning can also explain why some other previous studies did not demonstrate a degradation effect. For example, van Moorselaar, *et al.*[39] found that performance did not differ for a long-delay (1400 ms) non-cue condition and a short-delay (900 ms) non-cue condition, similar findings were also reported by Gressmann and Janczyk[70]. Because there is no degradation effect in our study, the mechanism underlying the retro-dimension-cue benefit is not simply due to protecting the representations of the cued dimension from degradation over time. In addition, we asked participants to remember two items in Experiment 3, which would not be a supracapacity set size for most participants, but we did not observe a reduction of the retro-dimension-cue benefit. This result implied that retro-dimension-cue benefit is also not simply due to protection from processing of non-reported dimension during the response phase. Thus, the retro-dimension-cue benefit could be caused by a combined mechanism of enhancing information about the reported dimension and removing information about the non-reported dimension.

We noted that the appearance of the probe display in neutral trials could give similar information to participants as a valid cue. For example, when the probe display included a color wheel in a neutral trial, the appearance of the probe display should cause an effect as giving participants a "Color" retro-cue. The appearance time of the probe display in the short-delay neutral condition is very close to the appearance time of a retro-cue in the valid condition. However, we observed that behavior performance was better in the valid condition than in short-delay neutral condition. Therefore, there may be different mechanisms between using a dimension cue (as the valid condition) and using a probe display (as the short-delay condition) to cue the target dimension. A similar result was observed in Souza, *et al.*'s[62] study. They asked participants to perform a recall task with a retro-object-cue. In the no delay condition of their study, the cue and probe display appeared at the same time, 1000 ms after the visual stimulus offset. In the delay condition, the retro-cue appeared 1000 ms after the visual stimulus offset, and the probe display appeared 2000 ms after the visual stimulus offset. Although participants needed to maintain the VWM representations a longer interval in delay condition (1000 ms in the no delay condition, 2000 ms in the delay condition), they found that behavioral performance was better in the delay condition than in the non-delay condition. Their results implied that after participants received the cue, they needed some time to use attention to adjust cognitive resource allocation, otherwise the appearance of the probe display would interfere the resource reallocation process. Unlike the change detection task, in the recall task used here, there were no new visual items covering the location of memory items when the probe display appeared. Thus the interference caused by the probe display was not simply due to new visual input. Consistent with previous studies showing that cognitive demands of the test can also interfere with VWM representations during maintenance[71], we suggest that the interference of a probe display in a recall task is caused by the cue and probe display appearing at the same time. This would result in the resource reallocation process, which is triggered by the cue, and the decision-making process, which is triggered by the probe display, competing for cognitive resources with each other, thus reducing performance on the recall task. Therefore, the appearance of the dimension-cue before the probe display can separate the resource reallocation process (dimension-weighting process) and decision-making process, avoiding cognitive interference from the probe display. This suggestion can explain why, in our Experiments 2 and 3, behavioral performance was much better in the valid condition than in the short-delay neutral condition. Thus, we also suggest that the retro-dimension-cue benefit was possibly caused by separating the resource reallocation process and the decision-making process. This makes our paradigm well suited for future researchers interested in exploring the mechanisms of the dimension-based selection of internal attention.

Object-based encoding and feature-based storing. In the present study, our results supported the feature-based storing hypothesis and rejected the objected-based storing hypothesis. This is in line with Bays, *et al.*[72] and Fougnie and Alvarez's[73] studies. In their studies, participants were asked to remember five to six double dimension items. The results showed a strong independence of errors between feature dimensions, suggesting participants could recall one feature accurately but forget the other feature of the same object, thus supporting the feature-based storing hypothesis. However, there are still some challenges to the feature-based storing hypothesis from recent studies. Marshall and Bays[74] found that task-irrelevant dimensions were encoded into VWM automatically when participants were asked to store a task-relevant dimension. This finding suggests the alternative conclusion that VWM encoding is an object-based rather than feature-based process. In Bays, *et al.*[72] and Fougnie and Alvarez's[73] studies, participants need to remember five to six double dimension items, as VWM capacity is limited, participants could not encode and maintain all items with perfect fidelity in their studies. Marshall and

Bays[74] suggested that the conflicting prior results of Bays, *et al.*[72] and Fougnie and Alvarez's[73] study may be due to involuntary failure or variability in the encoding process for each dimension, resulting in independent errors on recall. However, this explanation suggested by Marshall and Bays[74] does not account for the findings of our Experiment 3. In Experiment 3, participants only needed to remember two items, which could be encoded and maintained perfectly, according to previous research[57]. As a result, there should be little to no failure or variability in encoding for each dimension in our data. Yet we still observe results which are consistent with VWM storage at the feature level. Therefore, our study provides new evidence to support that view that VWM representations can be stored in a feature-based manner.

To be clear, our study does not challenge Marshall and Bays's[74] findings, and we have noted that their findings are also consistent with other studies[75]. Instead, we propose that participants encoded the memory items in an object-based manner involuntarily, but could store them in VWM in a feature-based manner voluntary. This explanation that could integrate both sets of previous findings, based on object-based encoding and feature-based storing. As we know, there may be independent mechanisms for the consolidation and maintenance of information in VWM[76], and we suggest that memory encoding and memory maintenance have different processing mechanisms. During the memory encoding phase (VWM consolidation), participants could process the VWM representation in an object-based way, such that task-irrelevant information of items would consolidate into VWM involuntarily. After the encoding phase is completed, the unit of VWM representations will become more detailed during the VWM maintenance process. VWM representations could be independently stored at the feature level, and participants could reallocate cognitive resources voluntarily to one given dimension according to task requirements. This explanation is also supported by Xu's[77] fMRI study, which found that participants initially encode memory items in an object-based manner, but gradually prune the task-irrelevant features during the VWM maintenance phase. In addition, Vergauwe and Cowan's[78] recent study showed that participants can flexibly store VWM representations as integrated objects or as independent features, according to task requirements. Although our study provides new evidence for feature-based storing hypothesis, this does not preclude the possibility that participants could store VWM representations in an object-based manner. Thus, we believe that in the future researchers could consider both object-based and feature-based mechanisms in VWM as not mutually exclusive, and potentially compatible. Our paradigm could be used to further explore object-based encoding and feature-based storage.

Summary and Conclusion

In summary, our results show a stable retro-dimension-cue benefit in VWM. These results demonstrated that participants can use internal attention to flexibly allocate cognitive resources to a particular dimension of VWM. We reject the possibility that the benefit is only caused by protection from degradation, or reducing the interference from processing of a non-reported dimension during the response phase. Our results further support the notion that visual features could be independent and stored separately from each other, such that objects have multiple feature levels of representation in VWM.

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Acknowledgements

This research was supported by grants from the National Natural Science Foundation of China (NSFC 31571123) to Q.L., (NSFC 31600883) to Z.H., and from the program of China Scholarship Council (CSC201508350054) to C.Y.

Author Contributions

C.Y., Z.H., T.R. and Q.L. conceived and designed the experiments. C.Y. and Z.H. performed the experiments. C.Y. and T.R. analyzed the data. C.Y., Z.H. and Q.L. wrote the manuscript. M.G. contributed to refine the language.

Additional Information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Ye, C. *et al.* Retro-dimension-cue benefit in visual working memory. *Sci. Rep.* **6**, 35573; doi: 10.1038/srep35573 (2016).