THE ROLE OF ATTENTION ON MAINTAINING VISUAL REPRESENTATIONS OF FEATURES AND BINDINGS

EREN GÜNSELİ

BOGAZİÇİ UNIVERSITY

2011

THE ROLE OF ATTENTION ON MAINTAINING VISUAL REPRESENTATIONS OF FEATURES AND BINDINGS

Thesis submitted to the

Institute for Graduate Studies in the Social Sciences

in partial fulfillment of the requirements for the degree of

Master of Arts

in

Psychology

by

Eren Günseli

Boğaziçi University

2011

Thesis Abstract

Eren Günseli, "The Role of Attention on Maintaining Visual Representations of Features and Bindings"

Visual working memory (VWM) maintains representations of objects that we perceive. It is a controversy whether maintaining all kinds of objects require equal amount of resources. Wheeler & Treisman (2002) suggested that maintaining bindings of features requires greater attention than maintaining features. In order to test this claim, in the present thesis, attention was manipulated during maintenance of VWM representations, and the effects of this manipulation were compared between trials in which memory was tested for features and bindings. Maintenance of features and bindings were disrupted equally from withdrawal of attention suggesting that maintaining features and bindings require attention equally. But there were individual differences depending on the VWM capacity of the participants. For high capacity individuals attention was selectively required for the maintenance of feature bindings.

Tez Özeti

Eren Günseli, "Parçalar ve Parçalar Arası İlişkinin Saklandığı Kısa Süreli Görsel Bellek Temsillerinde Dikkatin Rolü"

Algıladığımız cisimler kısa sureli görsel bellekte saklanırlar. Değişik özellikteki cisimleri saklamak için eşit miktarda kaynak gerekip gerekmediği tartışılan bir konudur. Wheeler ve Treisman (2002) parçalar arasındaki ilişkiyi saklamanın sadece parçaları saklamaya kıyasla ek kaynak gerektirdiğini savunmuştur. Bu iddiayı test etmek için, bu tezde, kısa sureli görsel bellek temsillerini saklama esnasındaki dikkat değişken olarak alınmıştır. Bellekte parçalar ve parçalar arası ilişki, dikkatin dağıtılması sonucu eşit miktarda kaybedilmiştir. Ancak katılımcılar arasında, kısa süreli görsel bellek kapasitesine bağlı farklılıklar gözlemlenmiştir. Yüksek kapasiteli bireylerde dikkat parçalar arası bilginin saklanması için gereklidir.

CONTENTS

CHAPTER 1

INTRODUCTION

We, as human beings, can represent the visual world in our brain. We probably think we have a highly detailed image of what we see. But think that someone blindfolds you just as you enter a room, would you remember all of the things you have seen in that room? Even if you remember some items conceptually, such as there was a chair, a table, and a cup at the table, will you remember their exact shapes and colors? Would you even remember the color of the walls? Visual working memory (VWM) is the system that helps us maintain representations of our immediate visual surroundings. VWM is limited in capacity (Cowan, 2001; Pashler, 1988). Although there is consensus on the existence of a capacity limitation, the basis of this capacity limit is not clear (for a review see Luck, 2008; Fukuda, Awh, & Vogel, 2010). Some researchers conceptualize the capacity in terms of bound object representations (e.g., Awh, Barton & Vogel, 2007; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), some in terms of features and their associations (Wheeler & Treisman, 2002), and some in terms of available attentional resources (Alvarez & Cavanagh, 2004; Bays & Husain, 2008). The debate on VWM capacity conceptualization is intertwined with the debate on the nature of VWM representations. For example, researchers who claim that VWM capacity is limited by a fixed number of objects, also claim that VWM represents bound object representations, with each object represented discretely (e.g., Awh et al., 2007; Barton, Ester, & Awh, 2009; Zhang & Luck, 2009). On the other hand, researchers who claim that VWM capacity is limited by the amount of available resources propose that resources are allocated across representations flexibly, based on factors like object complexity (Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Eng, Chen & Jiang, 2005; Wheeler & Treisman, 2002; Xu & Chun, 2005). In this thesis we investigate the role of attentional resources on VWM capacity for different types of visual information, namely features and bindings.

Visual Working Memory

Visual working memory (VWM) is the system that stores and manipulates visual representations (Philips, 1974). VWM is limited in capacity and duration (Pashler, 1988; Philips, 1974); yet, the source of this limitation is not clear. There are 3 major views on this issue: 1) VWM capacity is determined by the number of available slots for integrated object representations (Luck & Vogel, 1997; Vogel et al., 2001); VWM resources are limited and can be flexibly distributed, 2) either among an unlimited number of representations (Bays & Husain, 2008), 3) or among a limited number of representations (Alvarez & Cavanagh, 2004; Wheeler & Treisman, 2002). In order to further discuss the validity of these claims, I will first discuss how VWM capacity measured.

How to Measure VWM Capacity?

Most recent research on VWM assesses capacity using a change detection task (e.g., Luck & Vogel, 1997; Pashler 1988; Awh et al., 2007). In the change detection task, participants first *encode* items in the briefly presented memory array, and then *maintain* representations during the delay. Viewers need to establish the *correspondence* between items in the memory and the test arrays, and then perform a *comparison* between the presented stimuli and corresponding representations. After the comparison, they decide whether there is a change and respond accordingly usually by pressing keys (Fencsik, Seymour, Mueller, Kieras, & Meyer, 2002, Phillips, 1974)) (see Figure 1). Some researchers argue that detection and identification of the change are two separate stages with separate behavioral and neural markers. Not all detected changes can be verified, which then may result in erroneous responses (Hyun, Woodman, Vogel, Hollingworth, & Luck, 2008).

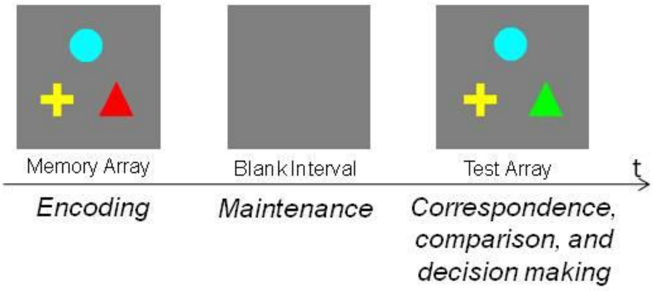

Fig. 1. A trial in change detection

The performance in change detection tasks can be measured simply by looking at accuracy level and response time (RT). Greater accuracy and faster responses mean better memory. In addition to accuracy, researchers have developed formulas to estimate VWM capacity. A formula derived by Pashler (1988) and revised by Cowan (2001) estimated the number of objects maintained, i.e., the capacity of VWM.

$$k = (H + CR - 1)N \quad (1)$$

where *k* is the capacity of VWM, H and CR are hit and correct rejection rates, respectively, and N is the number of items in the memory array.[1] The capacity estimate k depends on the assumption that VWM representations are maintained in an all-or-none fashion. According to this assumption, a subset from the memory

[1] See Appendix A for the derivation of *k* formula.

array is maintained and if the target is in that subset the participant can detect the change (unless they make a comparison error or key pressing error). Additionally, they can just guess the correct key by chance even if the target was not maintained in the subset. But some researchers claim that VWM representations are noisy, and participants might make mistakes during comparison due to this noise even if the target is maintained in VWM (Wilken & Ma, 2004). Furthermore, some research suggests that capacity is not limited by a fixed number of items, and that participants can maintain all items in a given array (Bays & Husain, 2008). In short, k formula has assumptions that are based on the fixed capacity models of VWM. Therefore I believe it should not be used in a study which investigates the capacity models of VWM.

Signal detection sensitivity (*d*') is another measure which is used to quantify the change detection performance (e.g., Johnson, Hollingworth, & Luck, 2008). The d' formula (Green & Swets, 1966; Macmillan & Creelman, 2005) is as following:

$$d' = z(H) - z(F) \quad (2)$$

where d' is the sensitivity measure of change detection, z is the transformation which converts hit rate (H) and false alarm rate (F) into z scores. Since it does not have any assumptions regarding the capacity conceptualization of VWM, I suggest d' is a more objective measure compared to k.

Based on the aims of the researcher, the following variables may be manipulated in change detection paradigms. The differences can be in the duration of presentations and delays (e.g., Luck & Vogel, 1997), the number of items in memory and test arrays (e.g., Vogel et al., 2001), the type of items used as visual stimuli (e.g., Alvarez & Cavanagh, 2002), and difficulty of changes in the test array (e.g., Awh et al., 2007; Wheeler & Treisman, 2002). In the following paragraphs I discuss each one of these factors.

The duration of the memory array should not be too short in order for participants to encode the stimuli, and should not be too long to allow the verbal labeling of items (Vogel, Woodman, & Luck, 2006). Similarly the duration of the blank interval should be in the range which enables measuring VWM rather than sensory memory (Phillips, 1977; Rensink, O'Regan, & Clark, 1997; Vogel, Woodman, & Luck, 2006) while not allowing representations to fade away from memory (Zhang & Luck, 2009).

In previous research the number of items in memory arrays, i.e., set size, was manipulated in order to determine the capacity of VWM (Vogel, Woodman, & Luck, 2001). Number of items in test arrays is another variant in change detection task. The number of items in the test array can either be the same with the memory array (whole-display) or just one (single-probe). The logic is the same with the partial report procedure of Sperling (1960); in the whole-display condition, perceiving items, establishing correspondences between test and memory arrays, and comparing them one by one takes longer and is thought to be harder compared to single-display condition. As a result, in whole-display trials, even if representations were maintained in VWM, during comparison they could be lost due to interference from the test display (Ceraso, 1985; Irwin, 1992; Wheeler & Treisman, 2002; Makovski et al., 2008, Sperling, 1960) or due to time based decay (Boduroglu & Shah, 2009). Therefore, whole-display procedures might underestimate the VWM capacity (Wheeler & Treisman, 2002). Still, it should be noted that whole-display presentations has some advantages over single-probe displays given that they provide greater spatial configuration cues especially for high ability individuals (Boduroglu & Shah, 2009; Jiang, Olson & Chun, 2000)

In order to manipulate the ease of change detection and to reach “purer” estimates of VWM capacity researchers have also varied the type of change (Awh et al., 2007). The test item and the corresponding memory item could be either from the same category of objects (both are Chinese Characters) which was called a *within-category change*. Or, they could be from different categories of objects (one item being a Chinese Character whereas the other being a shaded cube) which was called a *cross-category change*. Participants were more accurate in the cross-category than within-category change trials. Awh et al., concluded that change detection is harder when the memory and test items are similar. Detecting such a change requires one to have higher precision representations compared to the case where they are categorically distinct. Awh et al. concluded that using a cross-category change yields a purer estimate of VWM capacity compared to using within-category changes which underestimates VWM capacity as a result of comparison errors.

Type of change has been varied also to test *what* is maintained, in addition to test *how many* representations are maintained (e.g., Fencsik et al., 2002; Wheeler & Treisman, 2002). For example, the change in the target object can be through “replacement” of a new feature value (e.g., a new color or a new shape) which did not exist in the memory array (Figure 2). Or alternatively, the change can be created w through the “interchange” of two feature values of two objects. For example a red triangle and a blue square in the memory array may turn into a red square and a blue triangle (Figure 2). Wheeler & Treisman (2002) claimed that, in the replacement condition, maintaining only the features is enough for detecting a change. But in the interchange condition one must maintain the associations (bindings) between features.

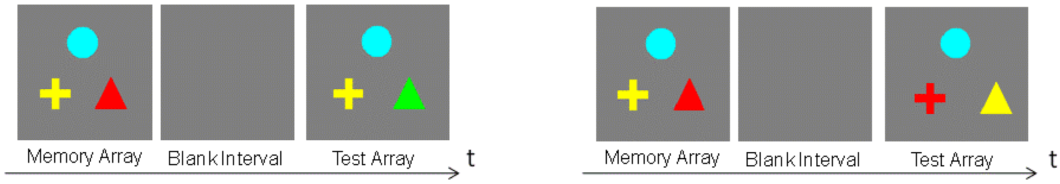

Fig. 2. (a) A trial in replacement condition. Green color replaces the red. (b) A trial in interchange condition. Yellow and red colors interchange their associations with

Nature of VWM Representations and Capacity

The nature of VWM representations and the capacity limits of VWM are two interrelated areas of research. For example, theories supporting VWM capacity is set by a fixed number of integrated-objects (e.g., Luck & Vogel, 1997) have arguments related to both the nature of representations and the conceptualization of VWM capacity. They argue that VWM maintains bound object representations, in which features of an object are integrated into a single unit. Furthermore, they claim that the capacity of VWM is set by 3 to 4 of these integrated units (Luck & Vogel, 1997; Vogel et al., 2001). Given that these two topics are intertwined and hard to discuss separately. In the following section, I will discuss models that have claims about both the capacity of VWM and the nature of representations limiting the capacity.

Research utilizing the visual change detection paradigm has yielded inconsistent sets of findings related to the nature of VWM representations and the conceptualization of VWM capacity (for review see Fukuda et al. 2010; Luck, 2008).

The conclusions can be clustered in three main models[2] supporting capacity concepts of *fixed-resolution representations and slots, variable-resolution representations and slots*, and *variable-resolution representations and flexible resources.*[3]

Models of Visual Working Memory Representations

Fixed Resolution Representations and Slots Models

Among proposals about the representation modality of VWM limitation, the most widely held view is the *fixed resolution representations and slots* models (e.g., Awh et al., 2007; Barton et al., 2009; Luck & Vogel, 1997; Vogel et al., 2001; Zhang & Luck, 2009). According to this model, VWM capacity is set by a fixed number of objects, around three to four, each occupying a distinct slot with a fixed resolution. Supporters of this model also claim that the limit is independent of the complexity of the objects maintained (e.g., Awh et al., 2007; Cowan, 2001, for a review; Luck & Vogel, 1997; Vogel et al., 2001). That is, whether VWM maintains only colors, or colored shapes of high visual complexity, the capacity is constant. Although it has been argued that with increasing complexity the capacity decreases below four objects (Alvarez & Cavanagh, 2004), Awh et al. (2007) argued that these reductions in capacity could be attributed to the relative difficulty of the comparison between complex objects compared to simple objects. They claimed that complex objects are similar to each other whereas simple objects are visually more distinct. As a result, participants are more likely to commit comparison errors during the test phase of a change detection task when the stimuli are complex objects.

[2] Although there are some differences in the claims within the models, for the purposes of the present paper, we divide them looking at their major assumptions.

[3] The terms *fixed-resolution representations and slots*, and *variable-resolution representations and resources* are from Luck (2008) review. The term *variable-resolution representations and slots* is derived based on Luck (2008) and other relevant work (e.g., Barton et al., 2009; Bays, Catalao, & Husain, 2009; Fukuda et al., 2010; Zhang & Luck, 2008).

Without changing the complexity of the objects maintained in VWM, Awh and colleagues (2007) manipulated the difficulty of comparison by varying the change type in the test array. As I mentioned in the previous section, the Awh et al. (2007) study had two types of changes; within-category and cross-category. Within-category changes are more difficult than cross-category changes because in the former the objects in VWM and test array are similar to each other, leading to more comparison errors, whereas in the latter the objects are distinct and easy to compare. In the cross-category condition, i.e., when the change is easy to detect, capacity estimates for simple and complex objects was similar. So according to Awh et al. (2007), the visual object complexity affected the comparison stage of the change detection task rather than maintenance stage of the VWM. Based on equal accuracy levels obtained for simple and complex objects in cross-category change trials, Awh et al. (2007) concluded that VWM capacity is set by a limited number of objects independent of the visual complexity of the representations.

Another piece of evidence supporting the *fixed resolution representations and slots* model comes from Luck and Vogel's (1997) seminal work. They tested change detection performance with different types of visual items; single features such as color, orientation, size, and gap, and objects formed by four of these features. VWM capacity estimate *k* was equal for items consisting of a single feature and items consisting of multiple feature dimensions (i.e., integrated objects consisting of up to four feature dimensions). Luck & Vogel (1997) concluded that the capacity of VWM is 4 integrated objects. Furthermore, they concluded that the number of features each object contains does not affect the capacity.

Another influential study which proposed that the capacity is independent of the object complexity was conducted by Zhang and Luck (2008). In this study, they used a color wheel task in which participants were asked to recall one of the previously studied colors and indicate it on a color wheel which consisted of the all possible color values (Figure 3). Zhang and Luck (2008) used the deviation of the responded color from the memory color to indicate the precision of participants' representations, i.e., if the responded color on the color wheel was close to the actual color presented in the memory array it meant that the participant maintained it with good precision.

Zhang and Luck compared the data against a number of models and determined that a two factor hybrid model provided the best fit for their results. In this particular model, the amount of error in the response was driven by the combination of 1) whether the item was in memory (represented via a normal distribution in the mathematical model) and 2) and the likelihood of committing a random pick (a uniform distribution in the mathematical model). According to this model, participants represented objects in discrete slots each with a fixed resolution (For an alternative account of performance in the color wheel task see Bays, Catalano, & Husain, 2009, further described below). They further bolstered this point by showing that a highly valid cue simultaneously presented with the memory array, did not reduce the resolution of the uncued colors. Furthermore, they claimed that the increase in the precision of cued colors can be explained by devoting more slots to the cued item, rather than devoting flexible resources. In short, Zhang & Luck (2008) supported the view that, VWM capacity is set by a fixed number of objects, each maintained in discrete slots.

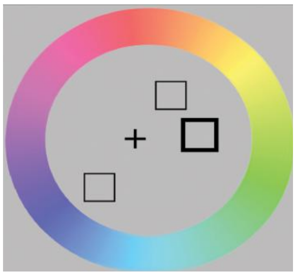

Fig. 3. Color wheel used in Zhang & Luck (2008) study.

Variable Resolution Representations and Flexible Resources Models

Compared to fixed slots models of VWM, variable resolution representations and flexible resources model of VWM claims that there is no fixed upper limits of slots. Rather, the capacity of VWM is only set by a limited resource which can be allocated flexibly to unlimited number of objects (Bays & Husain, 2008; Wilken & Ma, 2004). Bays & Husain (2008) tested the memory for location and orientation of visual items presented at the memory array. In test array a single item was displayed. Participants were asked the direction in which the item's location was displaced (or orientation rotated). As the set size decreased, participants were able to detect smaller changes which required maintaining detailed representations. Bays & Husain (2008) concluded that resources can be allocated flexibly among representations: representations at which greater amount of resources are devoted can be maintained with greater precision (see also Wilken & Ma, 2004).

Bays, Catalano & Husain (2009) further demonstrated that the results of the color wheel task used by Zhang & Luck (2008) could be accounted better with a model consisted with the flexible resourced model. Specifically, Bays et al. (2009) argued that performance on the color wheel task measured memory for color information as well as memory for color-location binding, because at test, the target was probed by marking its location. Participants might have committed errors even if they remembered all the colors, but misremembered which color was presented at the probed location.

Hybrid Models: Variable-Resolution Representations and Slots

Although supporters of *fixed resolution representations and slots* models claim that the capacity is independent of object complexity, some researchers have argued that the VWM capacity can be lower for complex objects (Alvarez & Cavanagh, 2004; Xu & Chun, 2006). *Variable-resolution representations and slots* models claim that there is an upper limit of 4 objects due to fixed number of slots. They also propose that object complexity can decrease the capacity below the upper limit because maintaining complex objects require greater resources than maintaining simple objects (Alvarez & Cavanagh, 2004; Eng et al., 2005).[4] In short, they propose that VWM capacity is set by both by a fixed number of objects and by limited resources that can be allocated flexibly among representations.

Alvarez & Cavanagh (2004) investigated VWM capacity in a change detection paradigm with objects of different levels of complexity. They defined object complexity as visual information load, and operationally defined it according to the visual search rate of that particular object among distracters of the same category of objects. They predicted that, processing rate of an object will determine the speed of detecting it in a visual search task. Visual search times were fastest for colored squares, followed by letters, line drawings, Chinese Characters, random polygons, and slowest for shaded cubes (Figure 4).

In a second experiment, they measured the change detection performance for these object categories. Visual complexity was inversely correlated with VWM

[4] It should be noted that Eng et al. (2005) attributed the reason of worse performance for complex objects not only to VWM limitations but also to perception difficulties during encoding.

capacity. Alvarez and Cavanagh (2004) estimated the capacity for colors around 4, but shaded cubes around 1. They concluded that, in order to maintain complex objects as precise representations allowing successful change detection performance, greater resources are required than maintaining simple objects. In short, Alvarez and Cavanagh's (2004) model supports the view that, resources in VWM are allocated flexibly, based on the visual information load of the object representations.

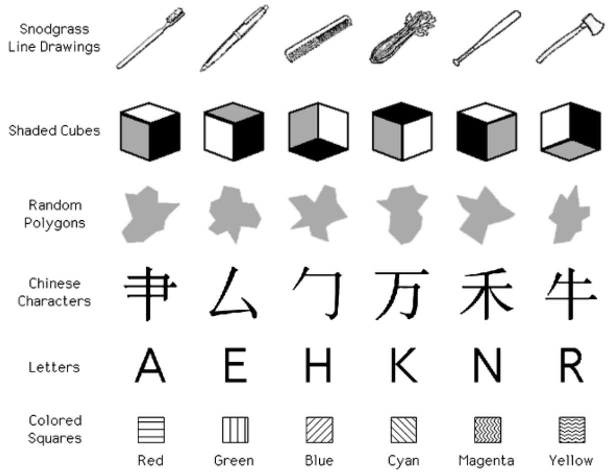

Fig. 4. The sets of objects used in Alvarez &Cavanagh's (2004) study.

Another evidence for *variable-resolution representations and slots* models comes from an fMRI study. Xu and Chun (2006) tested VWM capacity for simple and complex objects while recording activations in lateral occipital complex (LOC), superior intra-parietal sulcus (IPS), and inferior IPS, which have been found to be responsible in visual object perception and recognition, VWM capacity, and visual spatial attention respectively. Behavioral results of the study showed that estimated VWM capacity *k* was greater for simple objects (about 3) compared to complex objects (1.5). Considering the imaging results, superior IPS, and LOC activations increased with set size from 2 to 6 for simple objects, but was constant across set sizes for complex objects. In other words, activations in superior IPS, and LOC reflected the behavioral capacity estimates of VWM, dependent on object complexity, greater for simple objects compared to complex objects. On the other hand, activation in inferior IPS was independent of object complexity. It increased as the set size increased from 1 to 4, but reached a plateau at set size 4 both for simple and complex objects. In other words, capacity was the same for simple and complex objects. In short, the amount of activation in some brain regions associated with VWM capacity was correlated with object complexity, but not in some other regions. Based on these findings, Xu and Chun (2006) concluded that VWM capacity is set by both a fixed number of objects to divide attention between and by a total amount of visual information. In short, *variable-resolution representations and slots* models asserts that, when the objects are not too complex it is the number of slots which limit the VWM, on the other hand if the objects are complex, and their maintenance require too much resources, than it is the limited resources which defines the capacity. The important part of this conclusion for our purpose is that, maintenance of some representations requires more resources than others.

Wheeler & Treisman (2002) also claimed that the capacity is set by a fixed number of slots and also by attentional resources. But different than the models reviewed so far, they proposed that the representations in VWM are not bound object representations each constituting a slot. Rather, they claimed that features of an object are maintained in distinct storage units (see for a similar argument Xu, 2002b), and attention is required for maintaining the associations between the features of an object.

Wheeler & Treisman (2002) used a change detection paradigm to determine the role of attention in object maintenance. In their task, they manipulated the types of changes that could occur between the sample and test display. There were 2 types of change trials: replacement and binding. In the replacement condition (referred to as the “either” condition by Wheeler & Treisman, 2002) either a new color or a new shape replaced the old color or shape of the target object. In the replacement condition maintaining only the features of objects was sufficient to detect the change because a new feature which did not previously appear in the memory array replaced an old one (Figure 2). On the other hand in the interchange condition (referred to as the “binding” condition by Wheeler & Treisman, 2002), maintaining a bound object representation was necessary to detect the change. In the binding condition all features in the memory array were preserved in the test array, but they were combined in different ways. For example a yellow plus and a cyan circle form a yellow circle (Figure 2). Since no new feature entered the array, it was not sufficient to maintain only the features in order to detect the change. The other critical variable manipulated in this study was the type of test array. In the whole array condition, the same number of items existed in the test array and memory array. Whereas in single-probe condition only a single item was presented at test array (see Figure 2).

Wheeler & Treisman (2002) observed equal levels of accuracy for replacement, and binding trials in the single-probe condition. However, in the whole array condition, accuracy in interchange trials was lower than in the replacement trials. According to Wheeler and Treisman (2002) the greater attentional load of whole array condition caused a shift of attention from the representations to the items in test array. Since this shift selectively disrupted feature bindings but not feature only representations, they concluded that attention is particularly required for maintaining feature bindings.

The Role of Attention in Maintaining VWM Representations

The studies I have reviewed so far did not directly investigate the role of focused attention on VWM representations and capacity. In this section, I will discuss the relationship between attention and VWM capacity.

Rehearsal of VWM representations depends on focused spatial attention (Awh, Jonides, & Reuter-Lorenz, 1998). Focused attention to particular visual representation strengths its representation and provides an increase in change detection accuracy (Griffin & Nobre 2003; Lepsien & Nobre, 2007; Makovski, Sussman, & Jiang, 2008). These studies reveal the importance of attention for maintaining VWM representations. Even though previous research has investigated capacity differences for simple and complex objects in VWM, (Awh et al., 2007; Alvarez & Cavanagh, 2004; Xu & Chun, 2006) it has not directly considered the role of focused attention on how well objects are maintained in VWM. Given that attentional resources required for maintaining objects may differ based on visual information load (e.g., Alvarez & Cavanagh; Bays & Husain; Wheeler & Treisman, 2008), the role of attention on maintaining different types of visual information needs further inquiry.

There are two ways of manipulating attention during the maintenance of representations in VWM; attention can either be focused to or withdrawn from the stored representations. Recently, we investigated the effects of focused attention on maintaining representations in a visual change detection paradigm. We specifically tested whether focused attention on representations during maintenance results in an equal advantage for trials where either feature-only information (i.e., as in replacement conditions) or binding information (i.e., as in interchange conditions) needed to be stored (Gunseli & Boduroglu, 2010). A retro-cue was presented between the memory array and the test array pointing to the location of an object, allocating attentional resources to the representation previously presented at that cued location in the memory array. The cue was 100% valid. Retro-cue increased change detection performance compared to no-cue trials. More importantly, the increase was greater in the interchange condition compared to the replacement condition (Figure 5), indicating that binding information benefit more from attentional resources compared to features (but see Delvenne et al., 2010).

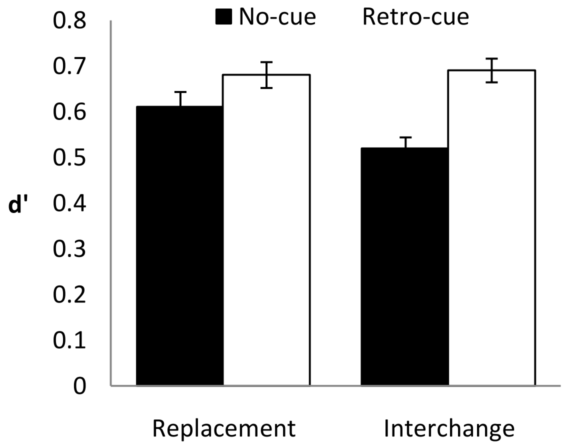

Fig. 5. The results from Gunseli & Boduroglu (2010) study. Change detection sensitivity (d') was greater for retro-cue compared to no-cue trials. The increase with the retro-cue was greater in interchange condition than the increase in replacement

These results are consistent with both *variable-resolution representations and slots* models and *variable-resolution representations and resources* models, supporting that some representations require more resources than others and can vary in resolution. Although the two models differ in their predictions of the nature of VWM representations, they overlap in their predictions at the allocation of resources among VWM representations. They support the view that resources can be flexibly distributed among representations, and the amount of resources devoted to a particular representation determines its precision.

Johnson, Hollingworth, & Luck (2008) investigated the role of focused attention on VWM representations by specifically engaging viewer's attention on a secondary task during the maintenance stage of change detection. They specifically compared whether withdrawing attention from integrated object representations and features resulted in similar losses in change detection accuracy. In the version of the task they employed, at the delay participants had to complete an attentionally demanding visual search task. If maintaining feature bindings required attention, then there should have been an interaction between the dual-task effect and the change condition (replacement and interchange), i.e., the visual search task should have impaired binding information more than feature information. But Johnson et al. (2008) observed no such interaction. The decrease in change detection performance with the visual search task was equal in replacement and binding conditions. As a result, they concluded that, maintaining feature bindings don't require more attention than maintaining features only.

But there was a critical difference in the procedure for the test of binding memory between Johnson et al. (2008) and Wheeler & Treisman (2002) studies. Wheeler & Treisman (2002) randomly changed locations of all objects at test array in order to enforce color-shape binding, making location non-informative. On the other hand, in the Johnson et al. (2008) study, objects occupied the same locations in both the test and memory arrays. Although Johnson et al. (2008) reasoned that, the lack of location scrambling will result in a purer comparison of VWM maintenance via eliminating the comparison difficulties of the task by enabling comparisons at known locations, the problem is, participants might had used the location information additional to shape-color bindings. Research have shown that keeping the locations constant between memory and test stages ensure easier maintenance of bound object representations (Hollingworth, 2007; Saiki & Miyatjusi, 2007; Treisman & Zhang, 2006), and provides an additional informative cue compared to when locations are varied (Poom & Olsson, 2009). Furthermore, in addition to rehearsal in VWM (Awh et al., 1998), retrieval from VWM also depends on spatial locations (Theeuwes, Kramer, & Irwin, 2010) which enable automatic correspondence between VWM and sensory input when locations are kept constant.

Given the alternative explanations for the Johnson et al. (2008) findings and the conceptually inconsistent findings between our earlier results (Gunseli & Boduroglu, 2010) and theirs, in the present project we want to re-address the issue of the role of attention on different types of visual working memory representations. Thus, we wanted to use a very similar design to the one in the Johnson et al. (2008) study and eliminate the possible confound that may have impacted the results. We argue that constant locations in test array might have led to use of location information in establishing a correspondence between features in memory and test array rather than relying on feature-feature bindings. In order to overcome this problem while still keeping the comparison stage simple (as in Johnson et al., 2008), in the present study we used a single-probe at the center of the screen. Since the target item is presented at the center of the screen, it makes location non-informative (Wheeler & Treisman, 2002). Furthermore, it does not make the comparison process overly demanding as scrambled locations of whole-arrays, which Johnson et al., (2008), argued might lead to “contamination” of memory assessment with comparison difficulties.

We claim that the visual search task is going decrease change detection performance due to attentional distraction (Johnson et al., 2008). More importantly, if maintaining associations between features requires attention, then the decrease should be greater in interchange trials compared to replacement trials, which test binding and feature information respectively (Gunseli & Boduroglu, 2010; Johnson et al., 2008; Wheeler & Treisman, 2002).

CHAPTER 2

METHOD

Participants

Forty-eight Bogazici University students participated in the experiment either voluntarily or for course credit. Four participants whose overall d' across four conditions was equal to or below .01 were excluded from analyses suggested that they were performing the task at chance (*M*= -0.03, std= .12).[5] I also excluded data from one participant who continued the experiment without getting the instructions.

Materials

Experiment was run in E-Prime 1.2. Stimuli were presented against a gray background on a 17-in CRT computer monitor at a viewing distance approximately 57 cm.

I used a change detection task to assess VWM capacity. Memory stimuli consisted of a total of 49 items made up of 7 colors and 7 shapes. Colors (RGB values in parentheses) were magenta (255, 0, 255), blue (0, 0, 255), cyan/aqua (0, 255, 255), green (0, 255, 0), yellow, (255, 255, 0), orange (255, 128, 0), and red (255, 0, 0). Items were of basic shapes (See Figure 6).Memory stimuli were approximately 1.74 visual degrees in diameter. Memory arrays consisted of three

[5] Note that d'=0 indicates chance level in a change detection task with 2 choices (same/different).

items[6] presented at the corners of an equilateral triangle centered at fixation with each side 80 pixels. Test arrays consisted of a single item presented at the center of the screen.

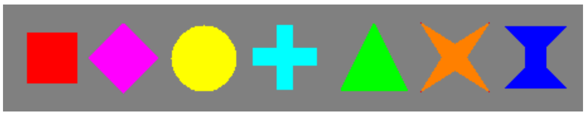

Fig. 6. Shapes and colors that are goint to be used in the present study.

The visual search array consisted of 0.53° x 0.53° outlined squares with one side open. All of the openings of the squares were either toward up or down except one square, i.e., the target, with an opening at the left or right side. Eight outlined squares were presented at a possible of 16 locations in the screen. Possible locations were the corners of four 2.27° x 2.27° squares, centered at the corners of a 3.89° x 3.89° square centered at fixation. The locations of the outlined squares never overlapped with the locations of the memory items.

Design

The experiment consisted of 5 conditions (performed in separate blocks) made up of either one of or both of 2 tasks; change detection (memory) and visual search. There were 2 memory-only (replacement; binding), 1 search-only and 2 dual-task (replacement; interchange) conditions. The order of the conditions was counterbalanced in 10 different ways (see Appendix B).

In order to equate durations and visual load in all conditions, the timelines of each trial in each condition were identical (see Johnson et al., 2008) (Figure 7). They

[6] Using set size as 4 in the pilot study, I have obtained below chance accuracies in many participants, especially in dual-task conditions. Accordingly, for the present study I specified the set size as 3 items.

began with the 100 ms presentation of the plus sign, followed by the 500 ms memory array. After the offset of the memory array, there was a blank interval of 500 ms. Then the visual search array was presented for 2,000 ms.. Following the offset of the search array, there was a second delay of 500 ms followed by the test array presented for a maximum of 3000 ms or till response.[7]

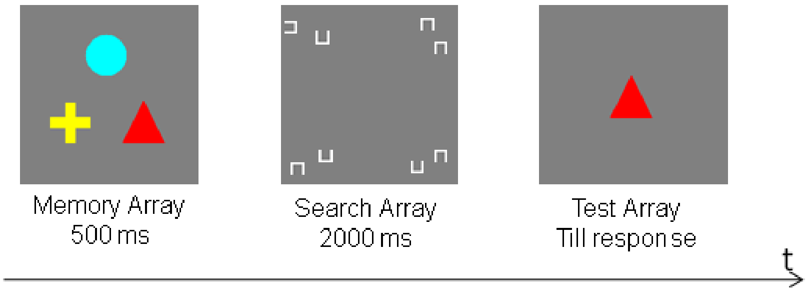

Fig. 7. A trial in the present experiment.

There were 48 trials in each condition. In memory-only conditions, the search array did not contain a target, i.e., all outlined squares contained an open side either on top or bottom. And in the search-only condition the item in the test array was always same with one of the items in the memory array. Change (different) and no change (same) trials were evenly and randomly distributed. Similarly, left and right responses were divided evenly and randomly across trials of the search tasks in each block (search-only, and dual-task conditions).

Procedure

Participants signed a consent form before the experiment, and filled the demographic form and answered the strategy questions after the experiment. They have taken an overall instruction phase before the experiment. Furthermore, before each

[7] All the durations are identical with Johnson et al. (2008) study.

experimental condition, participants were instructed about the requirements of that particular condition. They also completed a practice session of 20 trials.

Participants were told to attend only to the relevant arrays, which were memory and test arrays in memory-only conditions, visual search array in search-only condition, and all arrays in dual-task conditions. Participants were told to ignore the irrelevant arrays in single-task conditions.

In the memory tasks participants' task was to report whether the test item was the same with any one of the items presented in the memory array or whether it was different (a new object). They had a maximum of 3,000 ms to respond using the keyboard. They were instructed to strive for accuracy rather than speed. The key D indicated same (*Aynı* inTurkish) and K indicated different (*Farklı* in Turkish).

In the visual search tasks participants were instructed to find that the target (only square with an open side faced towards left or right) and indicate its open side using the keyboard. They were told to respond as fast as possible without losing accuracy. The key D indicated a left-opening (left means *sol* in Turkish), and K indicated a right-opening (right means *sag* in Turkish).

In order to prevent verbal rehearsal, participants were told to repeat aloud three digits monotonically[8] during the experiment. At the beginning of the experiment, they were listened a rate of 90 beats per minute as a reference. But they

[8] Twenty-three out of 48 participants performed the articulatory suppression with a metronome forcing participants to rehearse in the given frequency. But considering the comments of the participants informing that metronome voice was disrupting their performance too much, and the low change detection of the participants the remaining 25 participants were given a reference frequency at the beginning of the experiment. They later adapted a frequency which they felt comfortable and wasn't too slow in order to allow verbal rehearsal. An independent measures t-test between the two group were performed in order to compare the overall mean change detection d', mean change detection RT, mean search accuracy and mean search RT. All variables except overall change detection RT were equal (all *p*s > .13). But overall change detection RT was lower in the group without metronome (M = 908.63, SD = 218.97) compared to the group with metronome (M = 1086.42.63, SD = 163.81), $t(41) = 3.04$, $p = .004$, $\eta 2 = .18$).

were not forced to keep this frequency if they had difficulty in repeating the numbers.

CHAPTER 3

RESULTS AND DISCUSSION

Visual Search

Search performance is assessed with search accuracy and search RT. A paired-samples t-test was conducted to compare the mean search accuracy (percent correct) between each condition that involves the search task. Search accuracy in search-only condition (M = 97, SD =.03) was higher than search accuracy in dual-task interchange condition (M = 94, SD = .06), $t(42)$ = 3.15, p = .003, η^2= .19, and marginally higher than search accuracy in dual-task replacement condition (M = 95, SD = .04), $t(42)$ = 1.92, p = .062, η^2= .08. There was not a significant difference between search accuracies in dual-task interchange and dual-task replacement conditions, $t(42)$ = 1.56, p = .125, η^2= .05 (Figure 8). The results suggest that search accuracy is better when the search task is performed alone, compared to when it was performed in addition to a memory task.

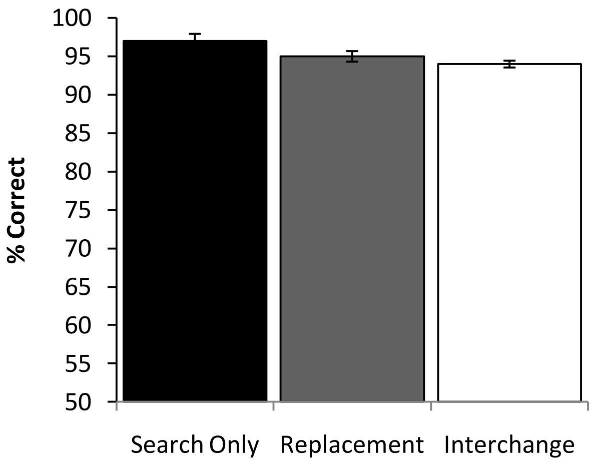

Fig. 8. Percent correct in visual search tasks of each condition (containing a search task). Conditions are shown in the x-axis. The error bars indicate the SEM's.

Search RT is another predictor of search performance, with faster RT's meaning better search performance. Only the trials with an accurate left/right judgment were taken into RT analyses. A paired-samples t-test was conducted to compare the mean search RT of each condition that involves the search task. Search RT in search-only condition (*M* = 960.09, *SD* = 150.21) was lower than search RT in dual-task interchange (*M* = 1016.54, *SD* = 186.09) condition, $t(42) = 2.12$, $p = .040$, $\eta^2 = .10$, and marginally lower than search RT in dual-task replacement condition (*M* = 993.04, *SD* = 126.37), $t(42) = 1.70$, $p = .097$, $\eta^2 = .06$ (Figure 9). Search RT in dual-task interchange and dual-task replacement conditions were equal, $t(42) = .96$, $p = .341$, $\eta^2 = .02$. The results suggest that search task is performed faster when it was performed alone compared to when it was performed in addition a memory task.

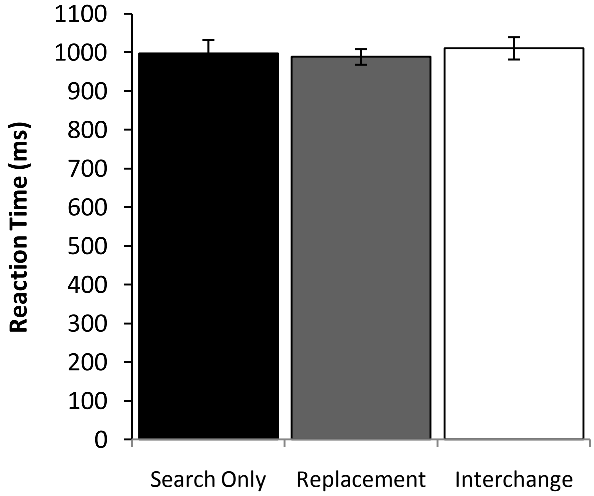

Fig. 9. RT in visual search tasks of each condition (containing a search task). Conditions are shown in the x-axis. The error bars indicate the SEM's.

Overall, results regarding visual search task suggests that, search performance was impaired when done along with the change detection tasks. Furthermore, although both the search accuracy and search RT in dual-task replacement and dual-task interchange conditions were not significantly different, the difference between search-only and dual-task replacement conditions being only marginal suggests that the impairment in the visual search task was greater in the interchange memory condition. This difference suggests that the interchange memory task consumes a greater amount of resources which is required for visual search.

Change Detection

The accuracy (percent correct) and change detection sensitivity (d') calculations representing the memory performance were compared across 4 conditions that involved the memory task. The accuracy produced the same pattern of results with d', for purposes of brevity, I report analyses based on d' only. Response time (RT) is another indicator of change detection performance. It is important to note that, in dual-task conditions, trials only with an accurate search response were taken into the memory performance analyses.

In order to compare the effects of dual-task cost on maintaining feature versus binding information a 2 x 2 analyses of variance (ANOVA) was conducted. Two independent variables were Task Type (memory-only; dual-task) and Change Type (replacement; interchange). The repeated measures ANOVA yielded a main effect of Task Type, $F(1, 42) = 22.75$, $MSE = .41$, $p < .0001$, $\eta_p^2 = .351$, a main effect of Change Type, $F(1, 42) = 12.64$, $MSE = .23$, $p = .001$, $\eta_p^2 = .231$. Most importantly, Task Type x Change Type interaction was not significant, $F(1, 42) = 1.12$, $MSE = .21$, $p = .30$, $\eta_p^2 = .026$, i.e., search task impaired memory performance equally in both types of changes (see Figure 10). Collapsed across change type, mean sensitivity (d') in memory-only tasks ($M = 1.07$, $SD = .61$) was greater than mean sensitivity in dual-tasks ($M = .60$, $SD = .42$), $t(42) = 4.76$, $p < .0001$, $\eta^2 = .35$. Collapsed across task type, mean sensitivity in replacement trials ($M = .97$, $SD = .42$) was greater than mean sensitivity in interchange trials ($M = .71$, $SD = .52$), $t(42) = 3.55$, $p = .001$, $\eta^2 = .23$.

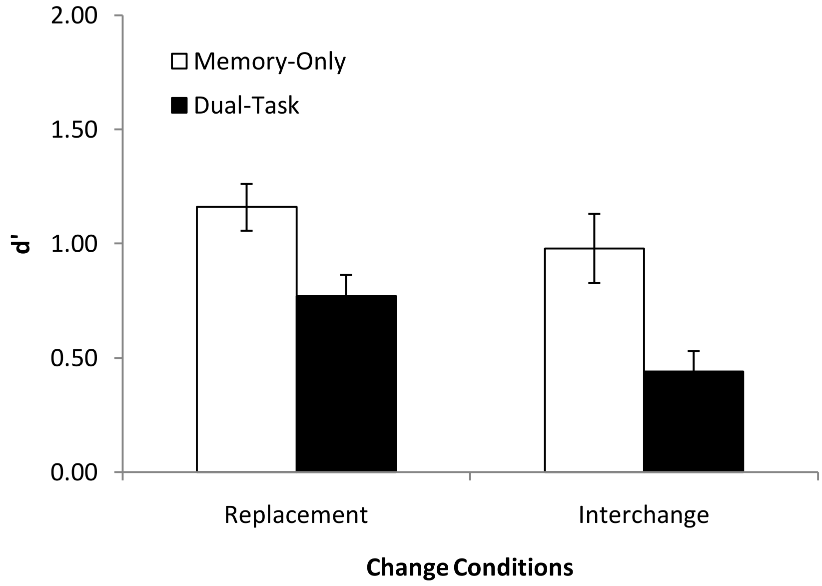

Fig. 10. Change detection sensitivity (d') across conditions (that involves a change detection task). The y-axis represents the d' values and the error bars represent the standard errors or the means.

In order to compare mean RT's across 4 conditions that included a change detection task, a repeated measures ANOVA was conducted. A 2 x 2 ANOVA on change detection RT yielded a main effect of Change Type, $F(1, 42) = 5.79$, $MSE =$ 13,445.50, $p = .021$, $\eta_p^2 = .121$. Main effect of Task Type, $F(1, 42) = .64$, $MSE =$ 13,734.08, $p = .43$, $\eta_p^2 = .015$ and Task Type x Change Type interaction, $F(1, 42) =$ 1.76, $MSE = 23{,}342.57$, $p = .19$, $\eta_p^2 = .04$, was not significant. Participants responded faster in replacement trials compared to interchange trials regardless of task type. Furthermore, RT in memory-only and dual-task trials was equal (Figure 11). RT analyses suggest that the results based on d' were not a result of a speed-accuracy tradeoff.

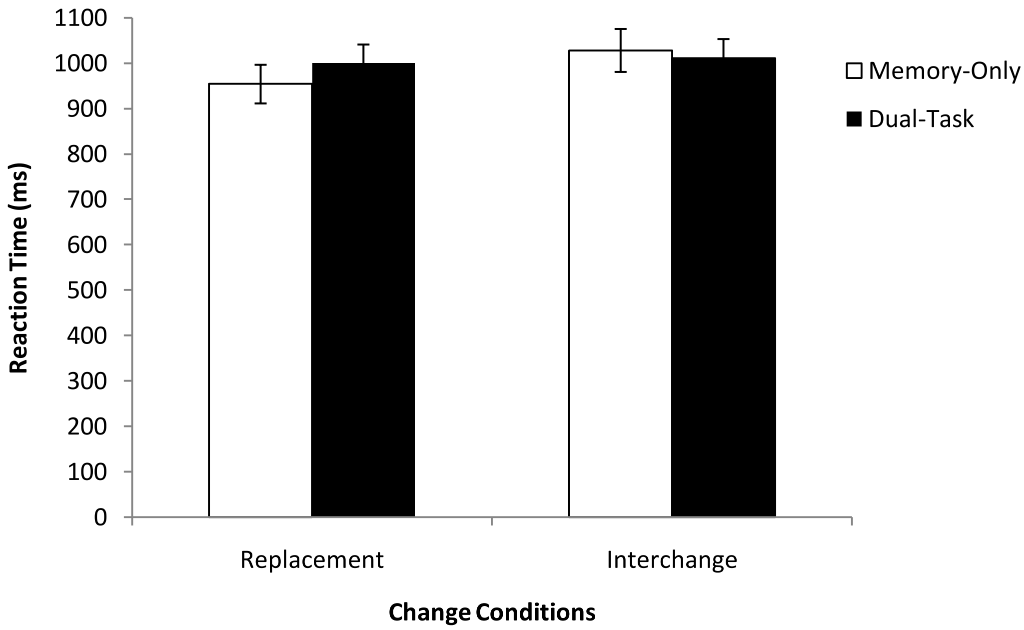

Fig. 11. Change detection RT across conditions (containing a change detection task). The y-axis represents the mean change detection RT, the error bars represent the standard errors of the means.

Although the d' was lower in interchange compared to replacement trials suggesting feature memory is superior to binding memory, the lack of an interaction indicates that feature and binding memory suffer equally from the withdrawal of an attention. However there are 2 alternative explanations coming from post-hoc analyses, (1) A Practice effect leading to a higher d' in the last two conditions (that involve a change detection task) compared to the first condition (that involves a change detection task), (2) near floor effect in the dual-task binding condition which I am going to discuss in detail later. Before that, I will present the results of an additional analysis based on individual differences.

Individual Differences Account

Gunseli & Boduroglu (2010) reported that memory for feature bindings benefit more from focused attention compared to feature memory. In a further analysis, participants were divided into 2 groups according to their overall d' based on a median split. Interestingly, the critical Change Type x Cue Condition interaction which was shown in the overall sample was absent in below median group. In order to test whether a similar pattern is evident in the present experiment we performed a median split and entered the resulting grouping factor as a between-subjects variable; a repeated measures ANOVA yielded no significant Group x Task Type interaction, $F(1, 41) = .93$, $MSE = .42$, $p = .34$, $\eta_p^2 = .022$, neither a significant Group x Change Type interaction, $F(1, 41) = 1.09$, $MSE = .23$, $p = .30$, $\eta_p^2 = .026$. Most importantly the Group x Task Type x Change Type interaction was significant, $F(1, 41) = 9.89$, $MSE = .18$, $p = .003$, $\eta_p^2 = .194$ In order to investigate the meaning of three way interaction in more detail, we analyzed data separately for high d' and low d' participants (Figure 12).

A repeated measures ANOVA on high d' participants' data showed a main effect of Task Type, $F(1, 21) = 15.26$, $MSE = .45$, $p = .001$, $\eta_p^2 = .421$, no effect of Change Type, $F(1, 21) = 2.66$, $MSE = .28$, $p = .118$, $\eta_p^2 = .112$, and most importantly a significant Task Type x Change Type interaction, $F(1, 21) = 7.96$, $MSE = .20$, $p = .010$, $\eta_p^2 = .275$, with a greater cost of search task on memory performance in interchange trials (decrease in d' = .83) compared to replacement trials (decrease in d' = .30). For the low d' group, a repeated measures ANOVA showed a main effect of Task Type, $F(1, 20) = 7.73$, $MSE = .38$, $p = .012$, $\eta_p^2 = .279$, and a main effect of Change Type, $F(1, 20) = 13.96$, $MSE = .17$, $p = .001$, $\eta_p^2 = .411$. Most importantly the Task Type x Change Type interaction was not significant, $F(1, 20) = 2.46$, $MSE = .15$, $p = .133$, $\eta_p^2 = .109$. In short, the high d' group showed that compared to the feature information, binding information is more dependent on attention, whereas the low d' group both types of information is equally dependent on attention for maintenance.

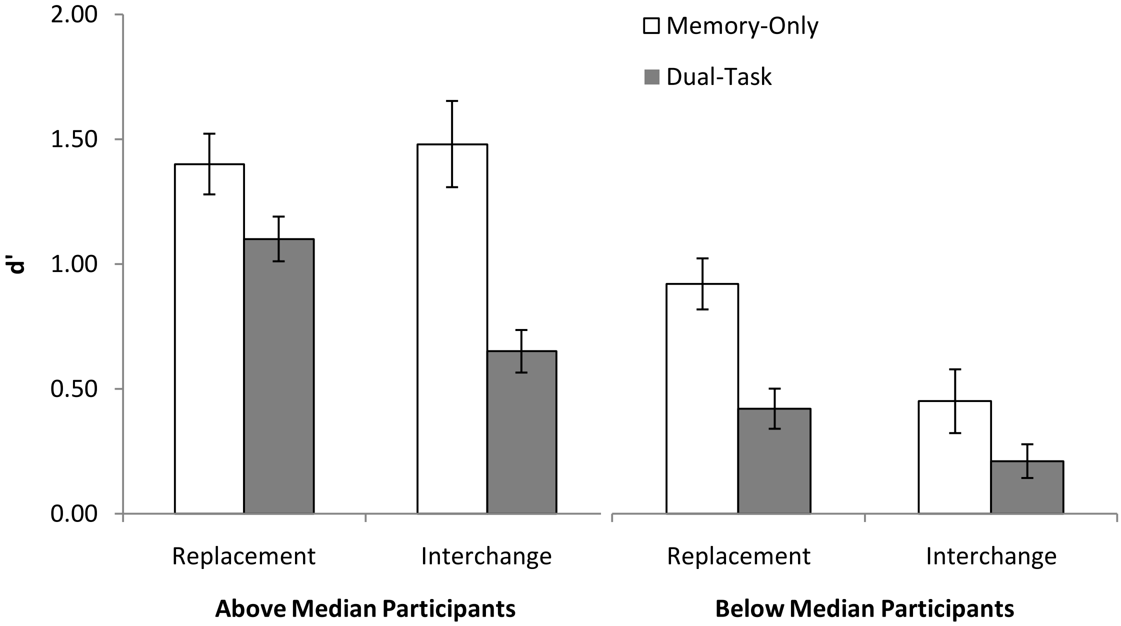

Fig. 12. Change detection d' values of above median d' (on the left panel) and below median d' participants (on the right). Change types are shown in x-axis and d' is shown in y-axis. The error bars represent the standard error of the means.

There were no individual differences in terms of search performance. In terms of accuracy, a repeated measures ANOVA with the Group as a between-subjects variable yielded a main effect of search condition (search-only; dual-task replacement; dual-task interchange), $F(2, 82) = 5.27$, $MSE = .002$, $p = .007$, $\eta_p^2 = .213$, but Group x Condition interaction was not significant, $F(2, 82) = .44$, $MSE = .002$, $p = .65$, $\eta_p^2 = .011$, accuracy was greater in search-only condition compared to dual-task interchange and dual-task replacement conditions for both high d' and low d' participants. In terms of RT, a repeated measures ANOVA with the Group as a between-subjects variable yielded a marginal main effect of search condition, $F(2, 82) = 2.81$, $MSE = 11886.28$, $p = .066$, $\eta_p^2 = .064$, but Group x Condition interaction was not significant, $F(2, 82) = 1.56$, $MSE = .\ 11886.28$, $p = .22$, $\eta_p^2 = .037$. Mean search response in the search-only condition was faster than mean search response in dual-task interchange condition for both high d' and low d' participants.

What is the reason behind this critical difference between the two groups in terms of change detection sensitivity? In a change detection task with a single-probe test display, Wheeler & Treisman (2002) observed equal change detection accuracy in replacement and interchange trials. On the other hand, with a whole array test display (which is more attention distracting) the interchange condition had a lower accuracy compared to the replacement condition. They concluded that the higher attentional demands of the whole array compared to the single-probe test display selectively impaired binding information but not feature information. In the present experiment, where a single-probe test display is used, high d' participants replicated the pattern in Wheeler & Treisman (2002). The sensitivities in the memory-only interchange ($M = 1.48$, $SD = .80$) and memory-only replacement ($M = 1.40$, $SD = .57$) conditions were equal, $t(21) = .52$, $p = .611$, $\eta^2 = .01$. But the results for low d' participants showed the pattern observed in the whole-array display condition in Wheeler & Treisman (2002), which was the attentionally distracting condition. For low d' participants, d' in the memory-only replacement condition ($M = .92$, $SD = .44$) was greater than the d' in the memory-only interchange condition ($M = .45$, $SD = .46$), $t(20) = 3.81$, $p = .001$, $\eta^2 = .42$. I claim that, the lower attentional resources of low d' participants resulted in a low precision (or fewer in number) maintenance of bindings even in memory-only conditions. As a result, the decrease in d' of interchange trials is restricted by the initial low d'. In line with this argument, for low d' participants, d' in memory-only interchange condition was equal to d' in dual-task interchange condition, $t(20) = 1.40$, $p = .178$, $\eta^2 = .01$. There was no drop in interchange d' from the memory-only to the dual-task condition. Also, the sensitivities in dual-task replacement and dual-task interchange conditions were equal, $t(20) = .22$, $p = .824$, $\eta^2 = .01$, i.e., the d' in an attentionally non-distracting condition with an interchange was equal to the d' an attentionally distracting condition with a replacement. In short, the low level of performance especially in the interchange trials in the low d' group prevented a large drop in performance in the dual-task conditions. In other words, for low d' participants, withdrawal of attention could not disrupt binding information because they had not form sufficiently detailed representations even for memory-only trials.

Training Effect

Keeping the individual differences (in the amount of VWM resources) account in mind, I still wanted to investigate the possible alternative explanations regarding the lack of the critical Task Type x Change Type interaction in the whole sample. When the change detection sensitivities were averaged based on the order with which each participant performed the change detection task (regardless of condition) there were signs of a training effect; d' was lower in the first condition compared to the fourth condition, $t(25) = 3.35$, $p = .003$, $\eta^2 = .31$, and the fifth condition, $t(25) = 2.67$, $p = .013$, $\eta^2 = .22$.[9] That is, participants performed worst in their first condition with a memory task independent of the particular condition. This result indicates that, the

[9] The mean and standard deviations are not given because the particular values are variable, depending on with which order the comparison was made. The reason behind this variability is that the search-only condition, which constitutes a missing value in change detection d', is in a different place in each counterbalance order. Thus, different comparisons yield different missing values, resulting in changes in means and standard deviations.

20 practice trials were not sufficient for participants to get used to the change detection task at the beginning of the experiment.

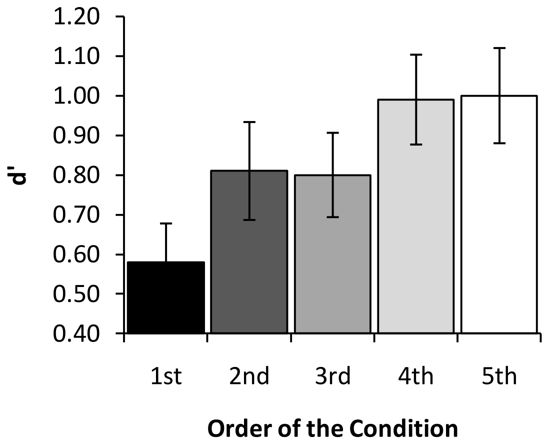

Fig. 13. The d' in change detection task based on order of the condition with which participants performed. The orders of the conditions are given in the x-axis and d' values are given in the y-axis. The error bars represent the standard error of the means.

In order to further test this claim, each participant was regarded as having only 4 conditions by taking the search-only condition out. A repeated measures ANOVA was conducted in order to test the effect of order for change detection performance. There was a main effect of order on d', $F(3, 123) = 3.54$, $MSE = .35$, $p = .017$, $\eta_p^2 = .08$ (Figure 14). More importantly, the effect of order was greater when the first condition was a dual-task condition compared to when it is a memory-only condition; a repeated measures ANOVA with Initial Task Type (the first condition with a change detection task being either a dual-task condition or a memory-only condition) yielded a significant Initial Task Type x Order interaction, $F(3, 123) = 3.24$, $MSE = .35$, $p = .025$, $\eta_p^2 = .073$. In short, participants performed better in the last conditions compared to the first condition especially if the first condition was a dual-task condition.

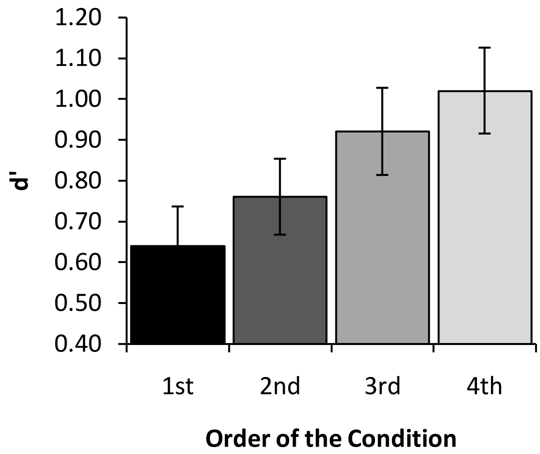

Fig. 14. The d' in change detection task based on order (When the search-only condition is taken out and participants are regarded as having 4 conditions rather than 5). The orders of the conditions are given in the x-axis and d' values are given in the y-axis. The error bars represent the standard error of the means.

Same pattern was evident for visual search task performance. A repeated measures ANOVA with 3 levels (search task performed at first, second, or third order) on search accuracy yielded a main effect of order, $F(2, 80) = 10.39$, $MSE = .01$, $p < .0001$, $\eta_p^2 = .206$. The search accuracy performed at the first order ($M = .93$, $SD = .06$) was marginally lower than the search accuracy performed at the second order ($M = .96$, $SD = .04$), $p = .023$[10], and the search accuracy performed at the third order ($M = .97$, $SD = .03$), $p < .0001$ (Figure 14). Similarly, a repeated measured ANOVA on search RT yielded a main effect of order, $F(2, 80) = 16.82$, $MSE = 17{,}163.80$, $p < .0001$, $\eta_p^2 = .296$. Responses in the search task were slower when given in the first

[10] Note that, with a Bonferroni correction of 3 comparisons the significance level becomes p = .16.

order (M = 1082.06, SD = .03) compared to the second order (M = 986.92, SD = .03), p = .001, and third order (M = 914.73, SD = .03), p < .0001. Furthermore, the search responses given in the second order were slower than the search responses given in the third order, p = .009. As the condition at which the participants performed the search task increases, responses get faster. In short, the effect of training is a factor that created an additional variability in change detection performance.

It is hard to suggest that this additional variability affected replacement and interchange trials differently and prevented the critical interaction pattern I had predicted. Nevertheless, it is a factor which contaminates the results (see General Discussion). Thus, in order to eliminate (or at least) decrease the effect of training on d' we ran an additional experiment (experiment 1B) with 2 counterbalance orders only in which the dual-task condition never preceded a single-task condition (which are the orders 4 and 6 - see Appendix B). The results of experiment 1B are given below after a brief discussion on another alternative explanation that is related to the practice effect.

Floor Effect in the Dual-Task Interchange Condition

There were 17 participants who performed at or below chance level (d' = 0) in at least one condition[11]. More importantly, this condition(s) was the dual-task interchange condition in 12 of the participants. That is, there were 12 participants who performed at or below chance level in the dual-task interchange condition. The chance level performance constitutes a lower border of d' because even if the participants perform without maintaining the VWM representations and respond

[11] Consistent with the practice effect, in 8 of the participants this condition(s) was (one of) the first condition(s) that contains a change detection task

randomly, they would perform at chance level. In other words, the chance level is the floor level in a change detection task with two forced choices. The interaction I have expected to observe depends on a greater decrease from memory-only to dual-task condition for interchange trials compared to replacement trials.. Twelve out of 43 participants performing at floor level in the dual-task interchange condition might have affected the overall pattern and prevented a greater decrease in dual-task interchange condition compared to the dual-task replacement condition.

Together, the 2 additional analyses above suggest that the change detection task in the first condition was performed less accurately than the later ones, especially when the first condition was a dual-task interchange condition. Furthermore, the d' was at floor in some of the participants. In order to overcome this problem, in experiment 1B, I ran more participants in 2 counterbalance orders that start with memory-only conditions and end with dual-task conditions and analyzed the data from that subgroup of participants.

CHAPTER 4

EXPERIMENT 1B

In the first experiment there was a strong practice effect, especially in orders starting with the dual-task conditions. In order to reduce the noise caused by the practice effect we decided to analyze the data of two counterbalance orders that started with single-tasks. There were only 2 orders (4^{th} and 6^{th} orders) in which a dual-task did not precede a single-task. Thus, these two orders which start with two memory-only conditions and end with two dual-task conditions were taken into analyses. In order 4, replacement conditions preceded interchange conditions and in order 6, interchange conditions preceded the replacement conditions thus the effect of order on change type was counterbalanced. In order to increase power, 2 additional participants were run resulting in 16 participants, with 8 in each order.

In order to test the practice effect on change detection d', search accuracy, and search RT, the order of the conditions were taken into analyses in one-way repeated measures ANOVA's. The order of the condition didn't have a main effect on the change detection d', $F(3, 45) = 1.04$, $MSE = .24$, $p = .39$, $\eta_p^2 = .07$, and on the search accuracy, $F(2, 30) = 2.53$, $MSE = .001$, $p = .10$, $\eta_p^2 = .14$, but have a marginal effect on search RT, $F(2, 30) = 3.14$, $MSE = 13{,}971.20$, $p = .058$, $\eta_p^2 = .17$. In short, the practice effect was reduced in experiment 1B. But still, there were conditions with chance level d'. Five participants had chance level d' in dual-task interchange condition, and 3 in memory-only interchange condition. There were no participants with a chance level d' in dual-task replacement and memory-only replacement conditions.

Visual Search

In order to compare the search performance across conditions a repeated measured ANOVA with the Search Condition as a within-subjects variable was conducted. In terms of search accuracy there was no main effect of condition, $F(2, 30) = .35$, $MSE = .001$, $p = .71$, $\eta_p^2 = .02$. Search accuracies were equal in the search-only condition, ($M = .96$, $SD = .02$), in the dual-task replacement condition ($M = .96$, $SD = .04$) and in the dual-task interchange condition ($M = .95$, $SD = .05$), all ps < .51. Similarly, in terms of search RT, there was no main effect of condition, $F(2, 30) = 1.24$, $MSE = 15{,}606.34$, $p = .30$, $\eta_p^2 = .08$. Search RTs were equal in the search-only condition, ($M = 1011.66$, $SD = 171.61$), in the dual-task replacement condition ($M = 944.54$, $SD = 102.24$) and in the dual-task interchange condition ($M = 962.28$, $SD = 171.61$), all ps < .21. In short, search performances in all conditions were equal.

Change Detection

In order to test the effects of Change Type and Task Type on change detection d' a repeated measures ANOVA was performed. A 2 Task Type x 2 Change Type ANOVA yielded no main effects of Task Type, $F(1, 15) = 2.05$, $MSE = .30$, $p = .17$, $\eta_p^2 = .12$, neither of Change Type, $F(1, 15) = 2.23$, $MSE = .25$, $p = .16$, $\eta_p^2 = .13$. Most importantly the Task Type x Change Type interaction wasn't significant, $F(1, 15) = 1.70$, $MSE = .12$, $p = .21$, $\eta_p^2 = .102$ (Figure 14). The results suggest that, the results in the first experiment were not due to the practice effect.

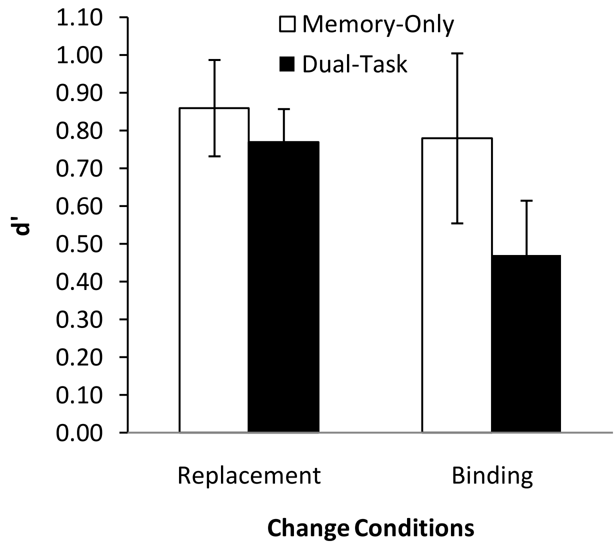

Fig. 14. Change detection d’ across conditions in experiment 1B. The error bars represent the standard error of the means.

A repeated measures ANOVA on change detection RT also yielded no effect of Change Type $F(1, 15) = .01$, $MSE = 12{,}204.63$, $p = .96$, $\eta_p^2 = .001$, no effect of Task Type, $F(1, 15) = .01$, $MSE = 7{,}897.70$, $p = .95$, $\eta_p^2 = .001$, and no Task Type x Change Type interaction, $F(1, 15) = 1.54$, $MSE = 8{,}290.86$, $p = .23$, $\eta_p^2 = .093$ (Figure 15).

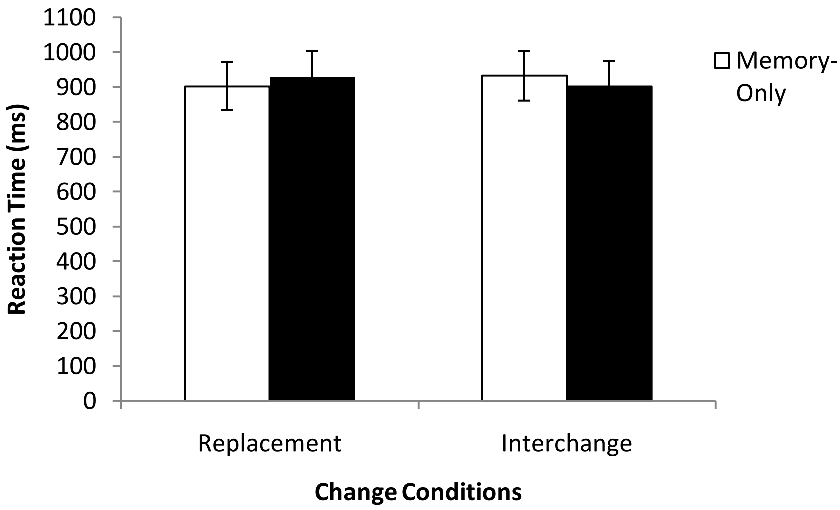

Fig. 15. Change detection RT across conditions (containing a change detection task). The y-axis represents the mean change detection RT, the error bars represent the standard errors of the means.

Individual Differences Account

Participants were divided into 2 groups based on their overall d'; above median (high d') and below median (low d') participants. A repeated measures ANOVA on mean d' was conducted with the Group (high d'; low d') as a between-subjects variable. There was no Group x Task Type interaction, $F(1, 14) = 3.08$, $MSE = .26$, $p = .10$, $\eta_p^2 = .18$. There was a marginal Group x Change Type interaction, $F(1, 14) = 3.63$, $MSE = .22$, $p = .078$, $\eta_p^2 = .21$. For low d' participants the interchange trials ($M = .19$, $SD = .19$) have lower d' than the replacement trials ($M = .60$, $SD = .21$), $t(7) = 3.12$, $p = .017$, $\eta^2 = .58$, but for high d' participants d' in interchange trials ($M = 1.07$, $SD = .69$) was equal to d' in replacement trials, ($M = 1.03$, $SD = .28$), $t(7) = .18$, $p = .86$, $\eta^2 = .01$. And most importantly there was no Group x Task Type x Change Type interaction, $F(1, 14) = 1.12$, $MSE = .12$, $p = .31$, $\eta_p^2 = .07$. The individual differences observed in the first was absent in experiment 1B.

CHAPTER 5

GENERAL DISCUSSION

In the present study I tested the effect of withdrawal of attention from VWM representations. The critical question was whether withdrawing attention from VWM representations would disrupt binding information more than feature information. Wheeler & Treisman (2002) suggested that maintaining feature bindings requires attention whereas maintaining features does not. Gunseli & Boduroglu (2010) observed that both types of information benefitted from focused attention, with binding information to a greater extend compared to feature information. On the other hand, Johnson et al. (2008) showed that feature and binding information was impaired equally with an attention distracting task that was performed during the delay/maintenance phase of a change detection task. Thus, they concluded that maintaining feature bindings doesn’t require attention.

One major difference between the 2 studies supporting the requirement of attention for maintaining bindings and Johnson et al. (2008) study is that the latter had a test array where all the items in the test array were located at the same locations as in the memory array whereas in the formers the locations of all items were randomly swapped in order to prevent the feature-location binding and force participants to maintain feature-feature bindings. Considering the literature claiming that maintaining location based information is easier than maintaining feature bindings (Hollingworth, 2007; Poom & Olsson, 2009; Saiki & Miyatjusi, 2007;

Treisman & Zhang, 2006), I suggested that the lack of a greater impairment in interchange trials in Johnson et al (2008) study might be due to the additional information provided by constant locations which participants relied on rather than maintaining feature-feature bindings.

In the present study I wanted to replicate the 1st experiment of Johnson et al. (2008) with a single difference; the items in the test array were not kept in identical locations as the memory array. Considering that Johnson et al. (2008) used constant locations rather than scrambled locations in order not to contaminate the memory measures with correspondence and comparison difficulties in test phase, I did not want to use scrambled locations neither. Thus, I decided to use a single-probe test display which provides a simplified comparison stage compared to whole array test display but at the same time eliminates the location cues provided by fixed locations of items.

Replicating the results of Johnson et al. (2008), I also did not observe an interaction between Change Type and Task Type; the impairment with the additional attention demanding search task was equal in replacement and interchange trials of the change detection task. But there were some facts which might have prevented the observation of the critical interaction. Participants were less accurate in change detection task in the first condition compared to the third and forth conditions especially if the first condition was a dual-task condition. Furthermore, there were 12 participants who performed at or below chance level in the dual-task interchange condition thus constituting a floor effect and preventing a greater decrease in interchange trials. Thus, in order to prevent the noise caused by the practice effect I collected more data in 2 orders in which a dual-task condition did not precede any of the single-task conditions. But the critical interaction between Task Type and Change Type was still not significant. The cost of the dual-task was equal for interchange and replacement trials. The results support the view that maintaining features and feature bindings require attention equally

The Practice Effect

I suggest that using a pure Latin Square design might not be necessary to provide statistical reliance in such a complex experiment where 5 conditions have completely different instructions and requirements. Given that there is a main effect of order on change detection d' and this effect is especially evident in orders starting with a dual-task, using all orders taken from Latin Square brings additional noise rather than eliminating the effect of order. Still, I accept that the practice trials being not sufficient for participants to get used to the experiment is a con for the present study. A future experiment in which sufficient training is performed before starting each experimental condition could be conducted in order to draw stronger conclusions. Nonetheless, using the two orders which progress mainly from easy to hard I observed that the order effect was not evident. Thus, testing the effects of experimental conditions became more reliable when I used only these two orders; results were not contaminated by an additional factor, i.e., order of the conditions. As a future study, the design might be conducted with practice sessions which are repeated until a specific accuracy is reached therefore eliminating the practice effect within the experimental conditions.

Individual Differences

Regarding the role of attention on maintaining feature bindings I observed a similar pattern of individual differences mentioned by Gunseli & Boduroglu (2010). They observed that, focused attention provided a greater benefit for binding information compared to feature information, and this interaction was stronger in high d' participants. Similarly in the present experiment (first), high d' participants displayed a different pattern than low d' participants; with the withdrawal of attention binding memory was impaired more than feature memory only in high d' participants but not in low d' participants. In low d' participants the impairment was equal for both types of visual memory.

What could be the reason behind this difference? As mentioned above, below median participants perform worse in interchange trials even in the memory-only trials performed with a single-probe test display. I suggest that, low d' participants might have insufficient VWM resources which are required to overcome interference from the test display (Makovski et al., 2008) and to maintain detailed representations in order to detect the changes (Awh et al, 2007). Engle and colleagues suggested that WM maintains information in the presence of interference and prevents distraction. Moreover, they claimed that there are individual differences in the WM capacity, thus in the ability to maintain information under distraction (e.g., Engle, 2002, Engle, Tuholski, Laughlin, & Conway, 1999). For low d' participants in the present experiment even in memory-only trials the distraction with the test array might be sufficient for interfering with the binding information. The change detection sensitivity might not have showed a greater impairment in the dual-task condition of interchange trials since they already were performing rather poorly in the interchange trials of the memory-only condition. On the other hand, high d' participants with greater VWM capacity performed equally well in interchange and replacement trials in the memory-only conditions, and binding information was selectively impaired with the attention distracting search task. Therefore, the difference regarding the critical Task Type x Change Type interaction between the two groups might be due to VWM resources which determine the change detection performance in memory-only conditions. The low d' participants might have had poor binding memory even in memory-only trials, thus didn't showed a greater impairment in interchange trials.

If this is the case, why couldn't we observe the similar individual differences pattern in experiment 1B? There might be two explanations. One explanation is that the results in the first experiment might be due to the additional variability caused by the practice effect and the floor effect in the dual-task interchange condition. In other words, the individual differences pattern might be a result of factors other than the experimental variables that are adding noise. Considering the low probability of getting a three-way interaction just to the noise in the data and that Gunseli & Boduroglu (2010) observed a similar pattern of individual differences I suggest a second explanation. The sample size might be rather small to get a three-way interaction. Although the three-way interaction was not significant, the pattern was in the right direction. For high d' participants in experiment 1B, the drop in d' from dual-task to memory-only trials is somewhat greater in interchange trials (d' = .62) compared to replacement trials (d' = .22) but rather equal for low d' participants (d' = -.01 and d' = -.05 for interchange and replacement trials respectively). Although not significant, the individual differences pattern is on the right direction in experiment 1B. A greater sample size would be appropriate to further investigate the individual differences account.

Summary

There were individual differences regarding the role of attention on maintaining features and bindings. For low capacity individuals attention was equally required for maintenance of features and bindings, whereas for high capacity individuals the attention requirement of maintaining feature bindings was greater than maintaining features. This results might be due to the fact that, for low capacity binding information being more vulnerable to interference and interfered by the visual load of test array even in memory-only trials. Or binding information might not be available (at least for all objects) at the first place even without being interfered. Overall, I suggest that, maintenance of binding information is more dependent on VWM resources compared to feature information.

Appendix A

Cowan's k

Direct quotation from Cowan (2001): "Upon examining a briefly presented array of N items, the subject is able to apprehend a certain fixed number of items, k. The apprehension of these items would allow a change to be detected if one of these k items should happen to be the changed item. Thus, with probability k/N, the change is detected. If the change is not detected, the subject guesses "yes, there was a change" with probability g. Thus, the formula for the hit rate H is: $H = k/N + [(N - k)/N]g$. If there is no change between the two arrays, and if the cued item happens to be an item that is included within the set k that the subject apprehended, then that knowledge will allow the subject to answer correctly that no change has occurred (and this is where our formula differs from Pashler's). If there is no such knowledge (for N – k items), then the subject still will answer correctly with a probability 1 – g, where g is again the probability of guessing "yes." Given that memory is used to respond in the no-change situation, it is useful to define performance in terms of the rate of correct rejections, CR. The assumptions just stated then lead to the following expression: $CR = k/N + [(N – k)/N](1 – g)$. Combining equations, $H + CR = 2k/N + (N – k)/N = (k + N)/N$. Rearranging terms, the capacity can be estimates as $k = (H + CR – 1)N$."

Appendix B

The Counterbalance Orders

The 10 counterbalance orders are listed below.[12] DT, MO, and SO indicate dual-task, memory-only, and search-only respectively. And R and I indicate replacement and interchange respectively.

Order 1: DTR – DTI – MOR – MOI – SO

Order 2: SO – DTR – DTI – MOR – MOI

Order 3: MOI – SO – DTR – DTI – MOR

Order 4: MOR – MOI – SO – DTR – DTI

Order 5: DTI – MOR – MOI – SO – DTR

Order 6: SO – MOI – MOR – DTI – DTR

Order 7: DTR – SO – MOI – MOR – DTI

Order 8: DTI – DTR – SO – MOI – MOR

Order 9: MOR – DTI – DTR – SO – MOI

Order 10: MOI – MOR – DTI – DTR – SO

[12] The orders are identical to those in Johnson et al. (2008) study. We would like to thanks Jeffrey S. Johnson for providing this information.

REFERENCES

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

Awh, E., Jonides, J., & Reuter-Lorenz, P.A. (1998). Rehearsal in Spatial Working Memory. *Journal of Experimental Psychology: Human Perception and Performance. 24*(3), 780-790.

Awh E., Barton, B, & Vogel, E. K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science, 18*(7), 622-628.

Barton, B., Ester, E., & Awh, E. (2009). Discrete resource allocation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 35*(5), 1359-1367.

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

Cowan, N., 2001. The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87-114.

Eng, H. Y., Chen, D., & Jiang, Y. (2005). Visual working memory for simple and complex visual stimuli. *Psychonomic Bulletin and Review, 12*, 1127–1133.

Engle, R.W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science, 11*, 19-23.

Engle, R.W., Tuholski, S.W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General, 128*, 309-331.

Fencsik D. E., Seymour T. L., Mueller S. T., Kieras D. E., Meyer D. E. (2002). Representation, retention and recognition information in visual working memory. *Abstracts of the Psychonomic Society, 7*, 69.

Fukuda, K., Awh, E., Vogel, E. K. (2010). Discrete capacity limits in visual working memory. *Current Opinion in Neurobiology, 20*(2), 177-182.

Griffin, I. C. & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience, 15*(8), 1176-94.

Gunseli, E., & Boduroglu, A. (2010). Maintaining feature bindings requires attention. Poster session presented at: Object, Perception, Attention, & Memory (OPAM). 18th Annual Conference of the Psychonomics Society; 2010 Nov 18; St. Louis, MO.

Green D. M., Swets, J.A. (1966) (as cited in Macmillan & Creelman, 2005). Signal detection theory and psychophysics. Oxford, England: John Wiley.

Hegarty, M., Shah, P., & Miyake, A. (2000). Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory and Cognition, 28*(3), 376-385.

Hollingworth, A. (2007). Object-Position Binding in Visual Memory for Natural Scenes and Object Arrays. *Journal of Experimental Psychology: Human Perception and Performance, 33*(1), 31–47.

Hyun, J., Woodman, G. F., Vogel, E. K., Hollingworth, A., & Luck, S. J., (2009). *Journal of Experimental Psychology: Human Perception and Performance, 35*(4), 1140–1160.

Johnson, J. S., Hollingworth, A., & Luck, S. J. (2008). The role of attention in the maintenance of feature bindings in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *34*(1), 41-55.

Irwin, D. E. (1991). Information integration across saccadic eye movements. *Cognitive Psychology, 23*(3), 420-56.

Lepsien, J., & Nobre, A. C. (2007). Attentional modulation of object representations in working memory. *Cerebral Cortex, 17*(9), 2072-2083.

Luck, S. J. (2008).Visual short-term memory. In S. J. Luck & A. Hollingworth (Eds.), Visual Memory (pp. 43-87). New York: Oxford University Press.

Luck, S. J., & Vogel, E. K. (1997, November 20). The capacity of visual working memory for features and conjunctions. *Nature, 390*, 279–281.

Macmillan, N. A., & Creelman, C. D. (2005). Detection Theory: A User's Guide (2nd ed.). Mahwah , N.J. : Lawrence Erlbaum Associates.

Makovski, T., Sussman R, & Jiang YV (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 34*(2), 369-380.

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics, 44*, 369–378.

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics, 16*, 283–290.

Poom, L., & Olsson, H. (2009). Binding feature dimensions in visual short-term memory. *Acta Psychologica, 131*, 85–91.

Rensink, R. A., O’Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science, 8,* 368–73.

Saiki, J., & Miyatjusi, H. (2007). Feature binding in visual working memory evaluated by type identification paradigm. *Cognition, 102,* 49–83.

Treisman, A., & Zhang, W. (2006). Location and Binding in Visual Working Memory. *Mem Cognit. 34*(8), 1704–1719.

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

Vogel, E. K., Woodman, & Luck, S. J. (2006). The Time Course of Consolidation in Visual Working Memory. *Journal of Experimental Psychology: Human Perception and Performance, 32*(6), 1436–1451.

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

Wilken P., Ma W. J. (2004). *A detection theory account of change detection. Journal of Vision, 4*, 1120–1135.

Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature, 440*, 91-95.

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

Zhang, W., & Luck, S. J. (2009). Sudden Death and Gradual Decay in Visual Working Memory. *Psychological Science, 20*(4), 423-428.