THE SAME OR DIFFERENT? CAPACITY LIMITATIONS IN VISUAL IMAGERY VERSUS VISUAL MEMORY IN THE SHORT-TERM

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Copyright Statement

Abstract

Research suggests that visual imagery and visual memory share similar underlying processes. One way to differentiate these processes is to understand if the capacity of imagination and visual memory are the same. To date, limited research has investigated capacity limits in imagination, and directly compared them to that of visual memory. This thesis aimed to provide estimates of imagination capacity and explore how this relates to the capacity of visual memory in the short-term (VMst). Collectively, experiments 1 and 2 explored capacity limits in imagination, visual working memory (VWM) and visual short-term memory (VSTM) using a novel paradigm that for the first time provided comparable estimates of capacity across these tasks. The key finding was that imagination capacity was lower than VWM and VSTM. Experiment 3 manipulated the time available to generate, update and maintain an image (imagination task) or encode, update and maintain an image (VWM task). Time did not influence performance in imagination or VWM. Experiment 4 explored whether the cuing methodology in the imagination task was responsible for worse performance than in the VWM task. None of the manipulations showed any specific influence on the imagination task suggesting this was not an important factor. Experiment 5 investigated whether the decision methodology favoured the memory tasks because of the inclusion of all the stimuli at test. The inclusion of all items benefited VSTM performance, whereas the reverse was true for the VWM task whereby performance was better when only a single item was presented at test. There was no impact on imagination performance. Experiment 6 explored the impact of object complexity on capacity in imagination, VWM and VSTM. Object complexity reduced VSTM capacity to the same level as imagery, however VWM capacity remained higher than imagery. Overall, the findings suggest that imagery is very similar to VWM, in terms of them being impacted similarly by manipulations. However, the capacity findings suggest that they may not be underpinned by identical processes. In contrast, imagery is less similar to VSTM as manipulations impacted these processes differently.

Acknowledgements

I would like to express my appreciation and thanks to my Director of Studies Duncan Guest, without your knowledge, guidance and support this would not be possible. I cannot thank you enough for giving me this opportunity - I will be *forever* grateful. On a lighter note, my mind still echoes your wisdom… “stop thinking and start doing!”, “keep it simple. It’s why 4 4 2 is the best formation” and “you’re tying yourself in knots”. Many thanks to my other supervisors Christina Howard and Thom Baguley, your positivity and knowledge has been invaluable. The next round is on me.

A special thanks to my partner Sabrina who has supported me beyond imagination. I love you. My son Ethan who inspires me to grow. Son, keep being inquisitive and keep your head in the clouds and your feet on the ground – I will love you forever and more. My mother, father, nannar, grandad and uncle who have shown me unconditional love over the challenging transitions of my life. Thank you for showing me how to love, how to accept and how to just be.

For the people who have supported me throughout my life, even in times of complete and utter anguish and tragedy, this one is for you.

“You only get out what you put in”

After 23 years of exile, Nottingham Forest are finally back in the Premier League - I dreamed of this day since I was young boy. 29/05/2022 – never forget.

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Publications

- Atkin, C., Guest, D., Howard, C. J., Baguley, T., & Baker, J. (2019). The Same or Different? Capacity Limitations in Visual Imagery versus Visual Perception of Simple Structured Objects. *The Cognitive Psychology Bulletin*, 4, 12 -13.

Conference Presentations

- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2021, September). The capacity of visual imagery, visual working memory and visual short-term memory for features. Virtual oral presentation (hosted by Oxford Brookes University), BPS Cognitive Society annual conference.
- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2020, July). The Impact of Test Format on Change Detection Performance in Imagery, VWM and VSTM. Virtual poster presentation, Experimental Psychology Society.
- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2020, April). The Same or Different? Capacity Limitations in Visual Imagery versus Visual Perception of Simple Structured Objects. Virtual poster presentation (hosted by the university of Kent), Experimental Psychology Society.
- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2019, September). The Same or Different? Capacity Limitations in Visual Imagery versus Visual Perception of Simple Structured Objects. Oral presentation, 21st conference of the European Society for Cognitive Psychology, Tenerife.
- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2019, August). The Stabilisation of Visual Information: The Influence of Extended Presentation Times on Visual Imagery and Visual Working Memory. Poster presentation, BPS Cognitive Society annual conference, Stoke-on-Trent.
- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2019, August). The Same or Different? Capacity Limitations in Visual Imagery versus Visual Perception of Simple Structured Objects. Oral presentation, BPS Cognitive Society annual conference, Stoke-on-Trent.
- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2019, February). The Same or Different? Capacity Limitations in Visual Imagery versus Visual Perception of Simple

Structured Objects. Oral presentation, Psychology PhD and DPsych conference, Nottingham Trent University.

- Atkin, C., Guest, D., Howard, C. J., & Baguley, T. (2018, August). The Same or Different? Capacity Limitations in Visual Imagery versus Visual Perception of Simple Structured Objects. Poster presentation, BPS Cognitive Society annual conference, Liverpool.

Prizes

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Chapter 1: Overview of the Thesis

This chapter gives a brief introduction to the project and an overview of each of the thesis chapters.

1.1 Introduction

Visual imagery and visual memory appear to utilise similar brain networks. However, limited research has investigated how similar the systems are in terms of capacity limits. Capacity limits of visual memory in the short-term (VMst) have been the focus of considerable research, but to date researchers are yet to ascertain the number of objects that can be simultaneously imagined. It is generally accepted that visual memory is capacity limited, with capacity estimates of ~ 4 items being derived from working memory models (Cowan, 2001; Luck & Vogel, 1997). One way to differentiate imagination and visual memory is to investigate their capacity limits. If imagination and visual memory are one and the same, then it should be expected that capacity will be similar. However, it might be that imagination suffers from more severe capacity limits than visual memory. The focus of this thesis is to investigate capacity limits in imagination and compare these limits to capacity of VMst using comparable behavioral tasks. To obtain estimates of capacity, mathematical models will be applied to the data. Taken together, the first two experiments explore capacity limits of imagination, VWM and VSTM. Experiments 3 and 4 investigate if methodological constraints limit performance in imagination and VWM. Experiment 5 examines the possibility of test array influencing performance in imagination, VWM and VSTM. Experiment 6 assesses object complexity in imagination, VWM and VSTM, and how this influences their capacities. Finally, individual differences are explored across all experiments.

A summary of each chapter is presented below.

1.2 Overview of the Thesis Chapters

Chapter 2: Visual imagery and visual memory literature review

This chapter provides an overview of visual imagery and visual memory literature. A definition of visual imagery is provided and the importance of imagery in day-to-day life is described. Theoretical accounts of visual imagery are then outlined. The chapter then goes on to discuss the neural basis of imagery, how imagery is measured and finally the current understanding of capacity limits in visual imagery is explored. The same sections are then applied to visual memory in the short-term, with each of the above-mentioned sections being discussed in turn.

Chapter 3: The relation between visual imagery and visual perception and visual imagery and visual memory in the short-term

Chapter 3 discusses the relations between visual imagery and visual perception and visual imagery and visual memory in the short-term. The first section compares neural evidence between visual imagery and visual perception, followed by the second section that compares behavioural evidence between the two. In both sections, similarities as well as differences are discussed. The same sections are then applied to visual imagery and visual memory in the short-term, with each of the above-mentioned sections being discussed in turn.

Chapter 4: Capacity models of visual memory

This chapter provides an overview on capacity models of visual memory in the short-term. The most influential capacity models are explained in relation to each other. The chapter then moves on to discuss the most common method for providing capacity estimates of visual memory. Three mathematical models of deriving capacity are presented, their relationships discussed and a justification for the use of one model throughout the thesis is provided.

Chapter 5: Experiment 1 and 2

Chapter 5 examines the first two experiments which investigate the capacity limitations of imagination and visual memory using a new paradigm to provide capacity estimates. Research suggests that like visual memory, visual imagery leads to activation in lower-level sensory areas (Albers et al., 2013; Lee et al., 2012; Reddy et al., 2010). However, due to reliance on top-down activation the activation patterns are more variable than in short-term visual memory tasks in which there is actual sensory input (Albers, et al., 2013). Set-size was manipulated in each task to enable modelling of capacity. Experiment 1 showed that imagination capacity was lower than known estimates of visual memory in the short-term (Cowan, 2001, 2005; Luck & Vogel, 1997; Zhang & Luck, 2008). Experiment 2 investigated imagination, VWM and VSTM capacity using comparable tasks and found that imagination was severely capacity limited in comparison to VWM and VSTM, with estimates of VWM and VSTM being similar.

Chapter 6: Experiment 3

This chapter examines the potential of methodological factors selectively limiting imagination capacity in Experiment 1 and 2. One of the limiting factors may be the time available to generate and maintain an image and to encode and maintain a memory. Experiment 3 manipulated the time available by doubling the time to imagine and remember objects from 2 seconds to 4 seconds. This experiment showed that time did not influence performance in either task.

Chapter 7: Experiment 4

Experiment 4 investigated the cuing methodology used to cue the to-be-imagined locations in the imagery task. Previous literature indicated that cuing imagination at increasing distances impacts performance (Bergmann et al., 2016; Borst & Kosslyn, 2010) and in Experiments 1-3 the cueing method for the imagination involved a cue outside of the grid in which stimuli were presented/imagined. It could therefore be that the capacity differences found between imagination and VWM in Experiments 1 and 2 could be due to the cuing method in the imagination task being less precise. Experiment 4 manipulated the size of grid in which stimuli were presented/imagined the sample array and the number of locations in the imagination and VWM tasks. Performance was impacted similarly for imagination and VWM, with performance differences remaining between the two tasks. Furthermore, the distance of the imagery cues (arrows) from the site where the image was to be presented was manipulated in the imagination task. No effect was found for arrow cue distance. Finally, an extra condition investigated the influence of arrow cues on the VWM task. No effect of introducing arrow cues on the VWM task was detected.

Chapter 8: Experiment 5

Chapter 8 investigates the influence of test array on imagination, VWM and VSTM performance. In Experiments 1-4, all to be remembered/imagined items were presented at test. This may have either favoured the memory tasks by presenting information as it appeared or disrupted the representation in imagination. It could therefore be that the capacity differences found between imagination and visual memory in Experiment 1 and 2 could be explained by the type of test array used. This experiment manipulates test array by task (Imagination, VWM, VSTM) such that at test, either a single item is presented, all items are presented, or all items are presented with a single item being cued. The data showed that test array influenced tasks differently. VWM performance was better for the single cue condition in comparison to both conditions that presented all items at test. Whereas, the reverse was true for VSTM, performance was better when all items were presented at test. In contrast, imagination performance was not significantly impacted upon by test array.

Chapter 9: Experiment 6

Chapter 9 examines the final experiment in this thesis, Experiment 6. The results of Experiment 2 shows that imagination capacity is more limited than that of visual memory in the short-term. Another way of assessing the commonality of the underlying processes is to examine how capacity in each task is influenced by the number of features. Previous research has shown that increasing complexity impacts capacity in both VWM and VSTM (Oberauer & Eichenberger, 2013; Wheeler & Treisman, 2002). Therefore, if imagination relies on the same underlying process as VWM, then imagination capacity should be impacted similarly to that of VWM. However, if the generation of more complex images requires extra resources, then an additional impact should be observed on imagination capacity in comparison to VWM. Results indicated that capacity was higher in VWM than imagination, whereas VSTM capacity was similar to VWM and imagination.

Chapter 10: Individual differences

This chapter explores the individual differences data across all experiments, creating a larger sample than any of the individual experiments. A number of questionnaires and Corsi block forward, and backwards tasks were explored in relation to task capacity estimates, task performance and vividness ratings. There are numerous findings of note. Interestingly, all three tasks (imagination, VWM and VSTM) strongly positively correlated, with the strongest relationship found between imagination and VWM, and the weakest between imagination and VSTM.

Chapter 11: General discussion

In this final chapter, a summary of the findings are provided for each of the 6 experiments. The findings of each experiment are then explored in relation to each other and in relation to previous literature. The findings are then discussed in the light of relevant theories. Finally, strengths, limitations and ideas for future research are presented.

Chapter 2: Visual imagery and visual memory in the short-term

2.1 Visual mental imagery

If a friend asks you where your home is in relation to a near-by landmark, you might develop a mental image and picture specific details of the route. This could be pictorial in nature and described as seeing with your 'mind's eye'. The ability to anticipate the future and recall past events; traveling through the mind space in our imaginations is something that make humans unique. For many, imagery plays an important role in day-to-day lives; whether it is thinking about the future or planning a move to navigate the environment. Visual imagery enables the creation of images in the mind that are incongruent with current visual stimuli and is distinctly different from that of visual perception whereby images in the mind are congruent with the current visual stimuli (Pearson & Kosslyn, 2013).

The involvement of imagery in mental functions has been well documented for well over a millennium (Galton, 1880). It is connected to a range of cognitive functions involved in sensory stimulation such as, episodic memory (Aydin, 2017), moral decisions (Amit & Greene, 2012), creativity, (Palmiero et al., 2011) and navigation (Bird et al., 2012). Furthermore, imagery partly accounts for the variation in individual differences associated with performance and capacity in a variety of cognitive tasks (Fukuda et al., 2010; Keogh & Pearson, 2014, 2017; Vogel & Machizawa, 2004; Zimmer, 2008).

Previous work has shown individual differences in vividness when people are asked to generate a mental image (Marks, 1973), such that some people can generate a strong and rich image, whereas others generate a dim image in their mind. Furthermore, some people are unable to experience images in the mind. This phenomenon is known as *aphantasia* (for review, see Zeman et al., 2010). Individuals with aphantasia cannot experience voluntary visual imagery and they perform significantly worse than controls in imagery tasks, thus demonstrating that imagery has a functional role in cognition (Jacobs et al., 2018).

Competing theories attempted to explain the nature of visual imagery. It has been widely debated as to whether imagery is symbolic, language-like (Pylyshyn, 2002, 2003) or more similar to perception, relying on depictive mental representations (Kosslyn et al., 2001). The imagery debate is focused on *how* the mental representation is stored. For an illustration of the symbolic versus depictive account, see Figure 2.1.

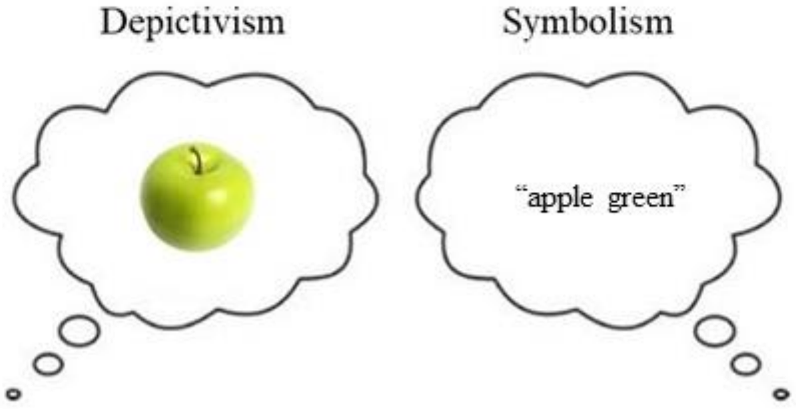

Figure 2.1. The two main theories: Depictivism (left) is pictorial in nature whereas symbolism (right) is language-like.

2.1.1 Theories of visual imagery

2.1.1.1 Depictive account

Kosslyn's depictive account states that information is stored similarly to that of a photograph where the depiction occupies a specific part of the visual space and has a functional role in the brain (Kosslyn et al., 2006). The depictive account was partially motivated by the possibility that visual imagery shares underlying mechanisms with visual perception (Kosslyn 1980; Kosslyn et al., 2006). Recent advancements in neuroimaging and the ability to objectively measure the fundamentally private nature of visual imagery has shed further light on the depictive account of visual imagery. The consensus is that there is commonalty in processing between imagery and visual perception (Pearson & Kosslyn, 2015). Indeed, recent neuroimaging studies investigating visual cortex function widely support the depictive account, suggesting similarities in neural activity between imagery and visual perception (see Pearson, 2019 for review of literature). The behavioural and neurological evidence provides support for Kosslyn's computational theory of visual imagery (Kosslyn et al., 2006). This approach aims to give a comprehensive account of the processes and subsystems that give rise to visual imagery. This model relies on four functions: image generation, maintenance, inspection and transformation.

Image generation can be formed from perceiving input from the outside world or from long-term memory (Hitch et al., 1995; Pearson & Logie, 2004). Irrespective of where the information comes from, imagery is generated in a topographically organised section of neural substrate, known as the visual buffer, that is said to be located in area V1 of the early visual areas (Kosslyn, 1994). However, a distinction is drawn between spatial and object imagery and how this information is processed. Kosslyn (1994) suggests that spatial imagery does not use the visual buffer for generation. Instead, an object map is developed in the spatial-properties-processing subsystem which is situated in the posterior parietal cortex (Kosslyn, 1994). This subsystem analyses spatial properties, such as location. In contrast, object imagery is generated in the visual buffer. Further evidence supports the dissociation between object and spatial imagery (Dawes et al., 2020; Keogh & Pearson, 2017). However, pure spatial and object imagery tasks are rare; often imagery tasks involve both spatial and object imagery, albeit to varying extents (Kosslyn et al., 1997). Moreover, research investigating ventral and dorsal activation in spatial and object imagery tasks found activation in both pathways, irrespective of the primary type of imagery (Ishai et al., 2000; Kosslyn et al., 1997; Lambert et al., 2002; Mazard et al., 2004). It is therefore difficult to separate spatial and object imagery, as often tasks that draw primarily on object processing require some spatial processing and vice versa.

Once generated the image is then maintained. According to Kosslyn, the maintenance of the object properties of an image is reactivated in an object-properties-processing system (Kosslyn et al., 2006). This system extracts visual information such as colour and shape. At the same time, the spatial-properties-processing subsystem maintains spatial properties of the image (Kosslyn et al.,1997). Active maintenance of the visual information is important as visual images can rapidly fade (Kosslyn, 1994; Pazzaglia & Cornoldi, 1999). Past research suggests that the fading of visual imagery is partly due to visual imagery sharing the same topographically organised substrate as visual perception (Kosslyn et al., 2006).

The two processing systems then converge to provide specific information about an object (for example, the colour of an item at a specific location). According to the theory, this integration process is achieved by a connection to the general associative memory system (Kosslyn et al., 2006). This system essentially matches the properties of the items to stored multimodal and amodal representations. If specific matches cannot be made to the stored representation, then distinct parts and characteristics of the object are best matched by an information lookup (also known as information shunting) process. This is a top-down process that passes information to other systems, that allows for the focus of attention (attention shifting) to shift to presumed parts and characteristics of the object. At the same time, this system passes information to the object-properties-processing system to prime the maintained representation with expected parts or characteristics (Figure 2.2).

Image inspection involves an attention window that shifts across the visual buffer which encodes visual object properties. In contrast, if only a spatial image has been generated, then the encoding of these properties (e.g., location) is extracted by the spatial-properties-processing subsystem (Kosslyn, 1994; Kosslyn et al., 2006). Image inspection works in tandem with image generation as inspecting an image requires generation of specific parts and properties of an object (Kosslyn, 1994). Nonetheless, image generation and inspection tasks largely produce distinct findings and are therefore distinct processes (Kosslyn et al., 2004).

Finally, image transformations are formed by altering the object map (i.e., mapping objects in space). In incremental stages, changes are applied to the mapping function formed between the object-properties-processing system and the visual buffer where the image is being represented (Kosslyn, 1994; Kosslyn et al., 2006; Thompson et al., 2009).

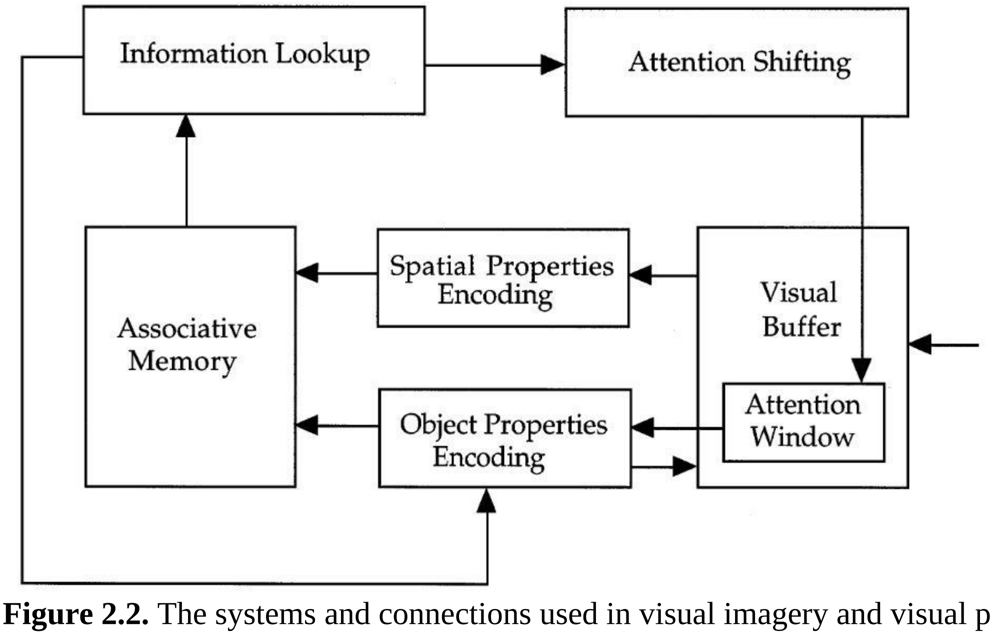

Figure 2.2. The systems and connections used in visual imagery and visual perception (Kosslyn, et al., 1997).

2.1.1.2 Propositional account

Pylyshyn (1973, 1981, 2002, 2003) argues that visual mental imagery is stored as a symbolic, language-like format and imagery is epiphenomenal (something that we experience but does not play a causal role in cognition). The early work of Pylyshyn (1978) discusses the idea that some cognitive processes are impenetrable, whereas others are penetrable. According to Pylyshyn, early visual processing is said to be an impenetrable cognitive state as beliefs and goals cannot affect the cognitive process. In support of this idea are the Ponzo and the Muller-Lyer Boerger visual illusions (Figure 2.3). These illusions continue to look like parallel lines of different lengths even when people know that the lines are in fact the same length. In contrast, penetrable states are viewed as cognitive processes that are influenced by beliefs and goals. Pylyshyn’s propositional account states that visual imagery is a penetrable state given that people have a large amount of voluntary control over the content of their imagery experiences, and that beliefs can alter supposed imagery processes (Pylyshyn, 1978). For example, Richman et al. (1978) demonstrated that it typically takes participants longer to mentally scan two points on a map when they are verbally informed that the distance is further rather than shorter, even when the physical distance between the points is the same.

Pylyshyn (2003) suggests that experimental findings that support the depictive account of imagery can be better explained as an interaction between task demands (e.g., asking participants to behave in a specific way) and *tacit knowledge* of the properties of visual experience. Tacit knowledge is described as having an understanding of how perceptual systems work. By accessing this knowledge, people are able to mimic what they would do in the perceptual world and simulate various properties of an object or scene by asking themselves what it would look like (Pylyshyn, 2002).

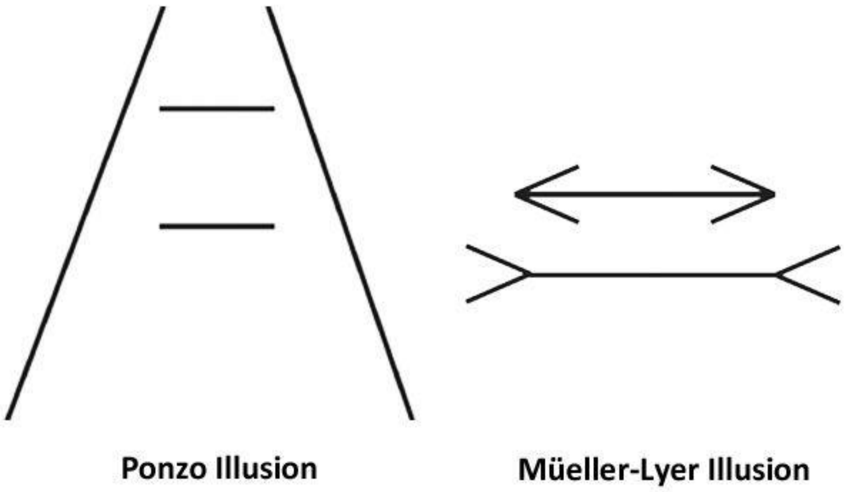

Figure 2.3. The Ponzo (left) and Mueller-Lyer (right) illusions show that even when the horizontal lines are the same length, they appear to be of different lengths.

2.1.2 The neural basis of visual imagery

A large neural network is involved in imagery with many describing substantial overlap between imagery and visual perception (for review, see Dijkstra et al., 2019). Pearson (2019) argued that imagery is visual perception in reverse (Figure 2.4). The imagery experience relies on an interconnected network including the frontal cortex, medial temporal lobe, early visual cortex and parietal cortex (Dijkstra et al., 2019; Ganis et al., 2004; Ishai et al., 2000; Pearson, 2019).

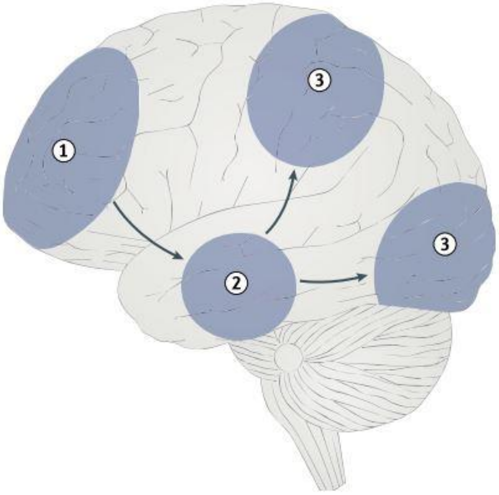

Figure 2.4. The Reverse Hierarchy Model of imagery taken from Pearson (2019). The image is first generated in frontal cortex (step 1). Subsequently, neural projections are sent to the medial temporal lobe where information is accessed (step 2). Content of imagery is then formed in the occipital cortex (step 3: right) and if location or movement are needed then the parietal lobe is activated (step 3: top).

According to Pearson's (2019) model, the process of generating an image begins in the frontal cortex (Figure 2.4: step 1). Activation and content specific information has been found in the frontal cortex when participants generate or manipulate an image in the mind (Ishai et al., 2000; Schlegel et al., 2013). For example, Ragni et al. (2020) used a multivariate pattern analysis (MVPA) approach with fMRI and found that imagined objects, letters and simple shapes could be decoded in the frontal cortex. However, further evidence suggests that the frontal region is more involved in the top-down control of image processing rather than in the exact content of the image (Dijkstra et al., 2019; Mechelli et al., 2004). Ishai et al. (2000) used fMRI to investigate content-related activity in different brain regions. They reported frontal cortex activation when imagining stimuli such as houses and faces, however they were not able to decipher content related activity. In line with these findings, the decoding of stimulus representations in the frontal regions are less accurate in comparison to decoding task identity (Hebart et al., 2018). Taken together, this evidence suggests that the frontal cortex plays more of a general executive role or organisational role rather than maintaining the exact content of the visual representation.

The second stage of the model proposed by Pearson (2019) suggests that the frontal cortex activates the medial temporal lobe (Figure 2.4: step 2). The medial temporal lobe houses the hippocampus which is widely known to be involved in memory encoding and storage. fMRI evidence supports the involvement of the hippocampus in imagery, with studies finding increased activation in the hippocampus when participants are asked to imagine scenes with increasing environmental boundaries (Bird et al., 2010). In addition, individuals with hippocampal lesion are poorer and less able to construct a spatially coherent imagined experience in comparison to matched control group (Hassabis et al., 2007; although see Miloyan et al., 2019). These findings support the role of the hippocampus in constructing an imagined experience.

The third stage of the Pearson's (2019) model posits that neural events continue onto the occipital cortices where the imagery content is formed (Figure 2.4: step 3). However, neuroimaging research exploring the activation of the early visual cortex in imagery has provided mixed evidence (see Pearson, 2020; Bartolomeo et al., 2020 for discussion). Some studies have found activation of early visual cortex during imagery tasks, whereas others did not find differences from baseline activity (Dijkstra et al., 2017; Ganis et al., 2004; Knauff et al., 2000; Spagna et al., 2021). It could be argued that inconsistent findings can be explained by methodological differences (task demands, complex vs simple objects) or individual differences in imagery strength and strategies (Keogh & Pearson, 2019; Pearson, et al., 2015). However, the rise of multivariate decoding has shed light on this issue with evidence showing that the content of a visual image can be decoded in the early visual areas such as area V1 and V2 (Albers et al., 2013; Bannert & Bartels, 2018; Cichy et al., 2012; Dijkstra et al., 2017; Naselaris et al., 2015). Furthermore, decoding algorithms that are trained on specific decoding of visual perception, visual memory, and visual imagery are all able to decode the content of an imagined object (Albers et al., 2013; Naselaris et al., 2015), thus suggesting that imagery is retinotopically organised in the visual cortices like visual perception (Klein et al., 2004; Slotnick et al., 2005). Other research has found a relationship between the size of V1 and the vividness of imagery. Imagery precision positively correlated with size of V1 whereas imagery strength negatively correlated with V1 size (Bergmann et al., 2016). Taken together, these findings suggest that the visual cortex plays a key role in encoding and maintenance of visual information with anatomy restricting and shaping aspects of the imagery experience.

According to the Pearson's (2019) model, if a representation has spatial properties, such as location and movement, then the parietal cortex is involved in imagery (Figure 2.4: step 3). Indeed, the parietal cortex activation has been reported when imagery tasks require participants to make spatial comparisons (Winlove et al., 2018). However, parietal cortex recruitment is not limited to spatial representations. For example, increased activity in the intraparietal sulcus has been found when participants were asked to focus on specific features of an imagined stimulus, such as the eyes or nose of a face (Ishai et al., 2002). Interestingly, content-related features that belong to different categories (letters, objects, and shapes) have also been decoded in the parietal cortex when imagining (Dijkstra et al., 2019; Ragni et al., 2020). Taken together, these findings suggest that the parietal lobe is not only important for spatial properties but also for encoding salient features in visual imagery.

2.1.3 Measuring visual imagery

The private nature of visual imagery makes it inherently difficult to measure. Extensive research on imagery has focused on self-report questionnaires that measure imagery vividness, control, and preference (for review, see McAvinue, & Robertson, 2007). For example, Vividness of Visual Imagery Questionnaire (VVIQ; Mark, 1973) measures the vividness of a participant's imagery when imagining scenes. It includes 16 items, in which participants rate their vividness on a 5-point scale. It was found that some participants reported stronger imagery vividness than others (Mark, 1973). Along with subjective measures of visual imagery, there is also a range of objective measures available (for review, see Pearson et al., 2013; also see, Pearson, 2014). Often subjective and objective measures are combined when investigating visual imagery. However, evidence suggests that subjective and objective measures of visual imagery are unrelated (for review, see McAvinue, & Robertson, 2007).

Many visual imagery studies that focus on objective measures aim to tap into the underlying cognitive structures and processes that are associated with Kosslyn's computational model of visual imagery by measuring response time and comparative or featural judgments (Kosslyn et al., 2006). Tasks that measure generation of visual imagery such as the Mental Clocks Task ask participants to decide which of two verbally presented clock times have the smallest angle between the hour and the minute hands on an analogue clock (Paivio, 1978). Response time data show that participants take less time to decide when the clock hands are further apart than when the hands are closer together. According to Kosslyn's theory, this finding demonstrates that participants generate an image in the mind to produce the answer. In contrast, Pylyshyn (2003, 2002) would explain this in terms of task demands (e.g., participants perform the task by accessing knowledge and questioning what the visual scene would look like). Other studies measuring maintenance of visual imagery use pattern tasks that require participants to visualise simultaneously presented squares within a matrix. Probed items are then presented in a blank matrix at test and participants decide if the probed items fall within the pattern that was visualised (Kosslyn et al., 1990). Other variations of this task have been developed such as the Cumulative Imagery Task (Avon & Sestieri, 2005). In this task participants are instructed to build up a pattern in their minds using black squares that are sequentially presented within a matrix. At test, a pattern is briefly shown, and participants are asked to decide if the pattern is the same or different to what they were asked to construct. Typically, in pattern tasks that require maintenance of visual representations error rates and response times increase with increasing patterns complexity (Dror & Kosslyn, 1994).

One of the most popular methods for measuring visual imagery in the last 10-15 years is binocular rivalry (Chang et al., 2013; Keogh & Pearson, 2011, 2014; Pearson, 2014; Pearson et al., 2008; Pearson et al., 2011; Sherwood & Pearson, 2010). This method is traditionally used in visual awareness (Tong et al., 2006), but is now widely employed as a measure of imagery *strength* (Keogh & Pearson, 2014, 2017; Pearson, 2014; Rademaker & Pearson, 2012). When used to measure imagery, typically participants are instructed to imagine one of two images (either red horizontal or green vertical gabor patches). After this, participants are then presented with rivalrous stimuli by presenting one percept to one eye (e.g., red horizontal gabor patch) and the other percept to the other eye (e.g., green vertical gabor patch) which causes a perceptual rivalry (binocular rivalry). Rivalry is the phenomenon that arises when visual input is inconsistent between eyes, essentially the brain cannot handle the fact the two eyes are telling it contradicting things. Typically, the imagined stimulus primes subsequent perception of that stimulus when viewing the rivalrous display compared to the other previously non-imagined stimulus (Figure 2.5). This indirect, objective measure of visual imagery *strength* moves away from other objective approaches that measure reaction time and comparative or featural judgments (Pearson, 2014; Pearson et al., 2015).

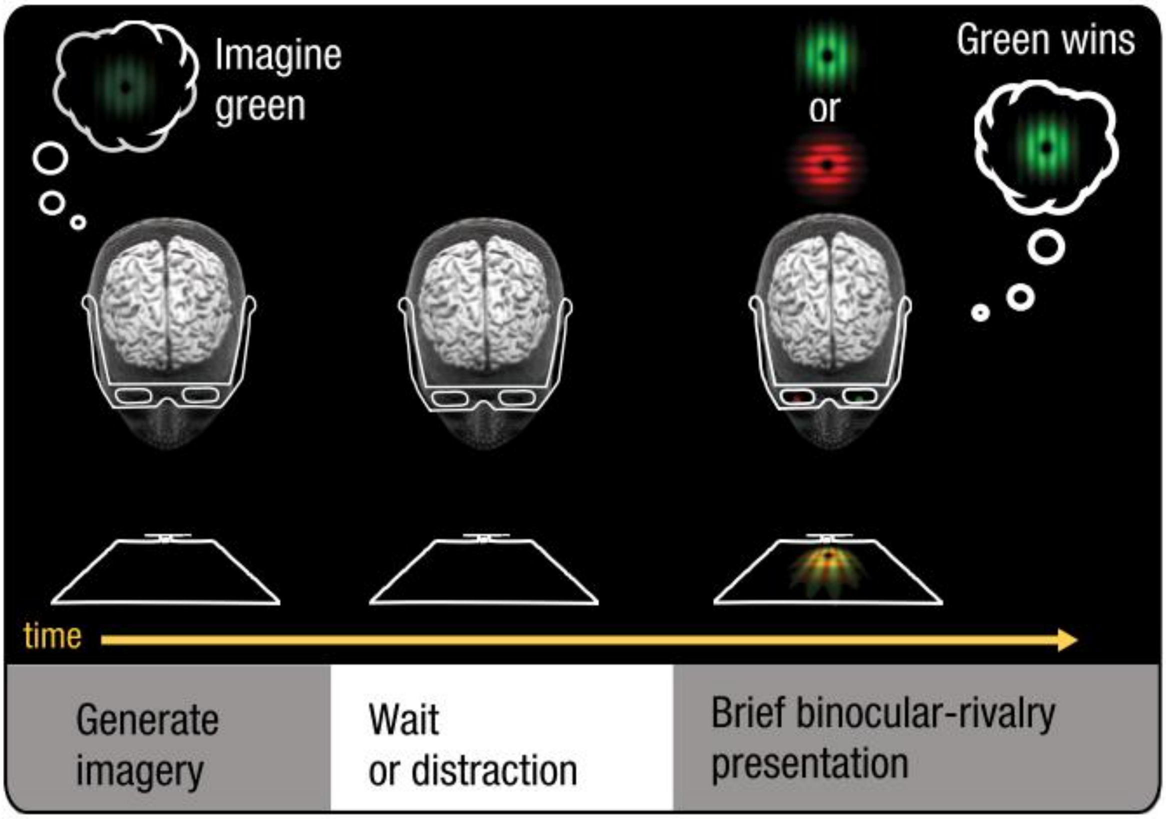

Figure 2.5. Binocular rivalry sequence of events. The participant is asked to imagine one of two images (in this instance the green gabor). After a short duration of time, the participant is presented with rivalrous stimuli by presenting a red horizontal percept to one eye and a green vertical percept to the other eye. In this instance, the green percept is dominant (wins) because the imagined green gabor primes the green perceptual gabor (Pearson, 2014).

2.1.4 Capacity limitations of visual imagery

The capacity of a cognitive system can be defined as the amount of information (e.g., number items) that can be held in the mind at any one time (Endress & Szabo, 2017). In 1983, Kosslyn, Reiser, Farah and Fliegel investigated image generation and construction in a series of experiments, showing that participants were able to imagine multiple images or units of information in the mind’s eye. They found that participants constructed an overall image of an animal by ‘gluing’ its separate parts, with time increasing as a function of the number of animal parts. Moreover, participants took longer to glue the individual parts together than imagine the animal as a whole. In a separate experiment, when imagining a scene, longer construction times were associated with increasing number of objects and greater distance between the objects (Kosslyn et al., 1983). Similarly, Kosslyn et al. (1978) found longer times were needed to scan larger items than smaller items. These studies demonstrated that individuals are able to generate images that contain multiple parts. This suggests that individuals have the ability to maintain multiple images in the mind's eye. However, these studies do not provide any information about the capacity limits of visual imagery.

Keogh and Pearson (2017) explored capacity limitations of visual imagery by measuring the impact of imagining multiple of items on subsequent binocular rivalry paradigm. Participants were instructed to use placeholder cues to imagine a varying number of red horizontal and green vertical gabor patches in order to examine the extent to which the imagination disrupted binocular rivalry (Figure 2.6). In experiment 1 participants viewed 1-7 achromatic placeholders that contained information about the colour and orientation of the to-be imagined gabor patches (e.g., two vertical grey dashes require participants to imagine a green vertical gabor patch). Stimuli for a binocular rivalry task were then randomly presented at one of the locations, and participants reported dominance (red-horizontal, green-vertical, or mixed) by button press. Experiment 2 was similar to experiment 1, but in experiment 2 the placeholders were coloured (green or red) to reduce colour memory. Nonetheless, both experiments found that imagery priming decreased as a function of set-size, showing that images become weaker when imagining more items. The procedure and stimuli for experiment 3 were the same as the previous experiments, with the addition of subjective ratings of vividness. Comparable to the findings of experiment 1 and 2, priming decreased as a function of set-size as did the vividness ratings. This indicates that there is awareness of decreasing quality when imagining more images. In experiment 4 generation time was manipulated (either for 6 seconds or 12 seconds) while in the earlier experiments the placeholders were presented for 6 seconds. It could be argued that the capacity function was due to larger arrays needing more time to initiate the priming effect. However, no priming differences were found between set-sizes in the time manipulation conditions (6 seconds or 12 seconds). This suggests that time is not a limiting factor in imagery generation and cannot account for the observed capacity function. Experiment 6 investigated the precision of visual imagery by tilting the rivalry display relative to what has been imagined by either 0, 11.5, 22.5, 30, or 37 degrees from horizontal or vertical. It was found that precision decreased with increase in set-size. This finding suggests that precision decreases when more images are imagined. Taken together, the findings indicate that visual imagery has capacity limits. There were, however, some limitations with the Keogh and

Pearson (2017) study. The binocular rivalry paradigm does not test what is currently being represented within a participant's imagination. Rather, the method establishes the degree of interference between the imagined item and the subsequent binocular rivalry task, with greater interference indicating a "stronger" imagination. Therefore, this does not enable direct estimation of the capacity of visual imagery. No precise estimates of capacity could be obtained, but capacity limitations inferred from the shape of the performance data (decreasing impact of imagery on binocular rivalry as set-size increased). Consequently, it remains to be investigated as to how many items can be maintained in visual imagery.

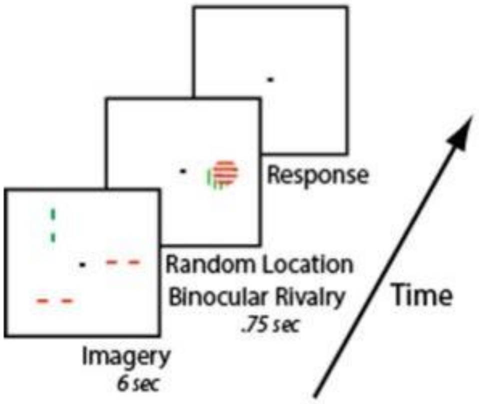

Figure 2.6. Participants were instructed to imagine either red horizontal or green vertical gabor patches between the placeholder cues. After which binocular rivalry was presented at any of the previously cued locations (Keogh & Pearson, 2017).

2.2 Visual memory in the short-term

Memory entails storing and retrieving information that has been experienced or learned. Consider a friend telling you their phone number and then asking you to repeat the numbers back to them in the same order. Recalling this kind of information is an example of a short-term memory (STM) task. STM has been defined as temporary maintenance of information over a short period of time (usually seconds) (Brown et al., 2005; Klingberg, 2010). Historically, a number of STM tasks simply required memorisation and recall/recognition. In response to this Baddeley and Hitch (1974) put forward the notion of working memory (although the term was used in the modal model – Atkinson and Shiffrin (1968), in which the STM is having to do work with the information within it). For example, if you were asked to recall the telephone number again, but this time you were asked to subtract one from each of the numbers, this would be an example of working memory (WM). Baddeley and Hitch’s (1974) model of working memory was an initial attempt to try to look at the different components within STM that enabled it to manipulate information. The term WM is typically defined as the maintenance of information plus manipulation (e.g., Cowan et al., 2005; Postle, 2006; Ranganath & D’Esposito, 2005). However, often the terms STM and WM are used interchangeably, with WM sometimes used for tasks requiring no manipulation and STM used in tasks requiring manipulation. Some researchers make no clear distinction between the two, and others suggest that WM has replaced the term STM (for a review, see Aben et al., 2012).

There is also uncertainty around the definitions in the visual domain of visual short-term memory (VSTM) and visual working memory (VWM) with these terms also often being used interchangeably. Frequently, tasks intended to measure VWM are more aligned with VSTM and vice-versa. For example, Courtney et al. (1997) required participants to retain an image of a face and indicate whether a test face matched the face held in memory. This task was described as a VWM task, yet there was no active manipulation of the visual information. Furthermore, Luck and Vogel (1997) described their seminal research on memory capacity as VWM. However, the set of experiments did not require participants to manipulate the visual information. Instead, this could be defined as a VSTM task and is often described as VSTM (Jiang, Olson & Chun, 2000; Sligte & Scholte & Lamme, 2008). For the purpose of this thesis, the term *visual memory in the short-term* (VMst) will be used to describe both visual short-term memory (VSTM) and visual working memory (VWM). However, when discussed separately, the term VSTM will refer to the short-term maintenance of visual information, whereas VWM will refer to short-term maintenance, plus the manipulation of visual information.

Previous research has demonstrated a segregation between visual and spatial working memory systems (Courtney et al., 1996; Logie, 2011; Zimmer, 2008). This segregation is supported by two parallel pathways: The ventral stream (i.e., the “what” pathway) is involved in processing object information such as shape, whereas the dorsal stream (i.e., the “where” pathway) is involved in processing spatial information such as location (Desimone & Ungerleider, 1989; Mishkin et al., 1983). Both pathways are supported by neuropsychological (e.g., Della Sala et al., 1999) and behavioural (e.g., Darling et al., 2009) evidence. However, isolating visual and spatial memory is difficult, and a range of studies have found interactions between the ventral and dorsal streams when maintaining and manipulating information (Koshino et al., 2005; Popov et al., 2018; Singha et al., 2006). This seems intuitive given that an object is inherently bound to a specific part of space and often tasks that draw primarily on object processing require some spatial processing and vice versa. Indeed, a large body of evidence suggests that spatial information is used to access visual features and aid decision during change detection tasks (Boduroglu & Shah, 2006; Jiang et al., 2000; Lin & He, 2012; Mou et al., 2008; Vidal et al., 2005; Woodman, Vogel, & Luck, 2012). Furthermore, memory representations are stronger when visual information (e.g., colour) and spatial information (e.g., location) are bound together (Wang et al., 2016; Zhao et al., 2022). Taken together, this evidence supports the argument against independent visual and spatial working memory systems and instead supports the idea that working memory is a unitary model (e.g., Cowan, 1999). For the purpose of this thesis, a distinction is not made between visual and spatial working memory, rather it takes the perspective that visual information and spatial information are represented in working memory in an integrated manner.

Interestingly, there are individual differences in the way information is remembered, with the format of memory representations influencing task performance (Keogh & Pearson, 2019). When participants are asked to describe what strategy they used to perform a memory task, they typically describe that their representations are either visual or phonological in form. Traditionally, it is thought that visual stimuli activate a visual/sensory store, and non-visual stimuli activate a phonological/propositional store. However, a recent review has called for a new framework that incorporates cognitive strategy (Keogh & Pearson, 2019). The proposed cognitive strategies framework suggests that memory should not be primarily defined by the type of presented stimuli. Instead, both the presented stimuli and the cognitive strategy used to complete the task should be considered. For example, the presentation of visual stimuli can be encoded and represented in a phonological/propositional form rather than a visual form. Additionally, in some tasks performance is better when using visual representations rather than phonological/propositional representations and vice-versa (e.g., Corsi block task vs digit span task). Therefore, the type of strategy used to perform a task can partly explain the variation in an individual’s ability to remember information (Keogh & Pearson, 2011, 2014 Vogel & Machizawa, 2004). Research attempted to explain how information is encoded, stored, and manipulated in the mind (for review, see Logie et al., 2020). A variety of theoretical models have emerged since the 1950s and 1960s that have attempted to explain memory in the short-term (Cowan, 2014; 2017; Logie et al., 2020).

2.2.1 Theories of visual memory

2.2.1.1 The Multi-component Model

One of the most prominent models over the last few decades has been the multi-component model (MCM, e.g., Baddeley & Hitch, 1974; Baddeley, 2000, 2007). This coordinated online cognition model separates components for storage and processing. The original MCM has three distinct memory subsystems which are the central executive, the phonological loop, and the visuo-spatial sketchpad (Baddeley & Hitch, 1974) with more recent theories of the MCM proposing an episodic buffer (Baddeley, 2000, 2007). Typically, the central executive is defined as a general task control mechanism that works closely with the episodic buffer, which is a multimodal store that holds integrated representations of short-term memory subsystems and is involved in long-term memory. Furthermore, the episodic buffer is said to aid with binding of information both between and within the subsystems of the phonological loop and the visuo-spatial sketchpad (Hitch et al., 2020). The phonological loop is a temporary store of verbal information, whereas the visuo-spatial sketchpad is a temporary store of visual information. The visuo-spatial sketchpad has been separated further in more recent MCM theories, with some stating that the visuo-spatial sketchpad can be broken down into separable stores and mechanisms for visual and spatial information (Logie, 2011). The visual aspect comprises of both the visual buffer and the visual cache which are two separable systems (Cocchini et al., 2002). The visual buffer is associated with the generation of low-level visual representations in the mind (Borst, Niven & Logie, 2012), while the visual cache is a passive store that stores visual appearance of objects such as colour or the pattern of objects (Logie, 1995, 2003, 2011). However, these two systems are not completely separable. Evidence suggests that visual information is transferred from the visual buffer to the visual cache where the image is then maintained (Borst, Niven & Logie, 2012; Logie, 2003). In addition, some researchers suggest that there is an additional system, named the inner scribe. The inner scribe is said to be an active component that is involved in dynamic processing and works by rehearsing information within the visual cache (Logie, 1995, 2003; see also Logie & van der Meulen, 2009). Akin to the model proposed by Baddeley (2002, 2007), these components are similarly associated with that of the central executive and the episodic buffer (Logie, 2011).

2.2.1.2 Embedded process approach

The embedded process model has been amended over many years (Cowan, 1988, 1999, 2005, 2008, 2011, 2016) to account for numerous empirical findings within a single framework. The embedded process model postulates that incoming sensory stimuli activate a short-term sensory store that last for a short duration of time (several hundred milliseconds) after the stimulus has disappeared from the environment. Once registered, this short-term store activates elements of long-term memory, with a small amount of the activated features then being held in the focus of attention (Logie et al., 2020). The amount of information that can be typically held within this focus of attention is between three and five units (Cowan et al., 2004; Cowan, 2005; also see Oberauer 2002, for an extension of Cowan's 1999 model that includes a single item focus of attention). This subset of features is held temporarily in a heightened state of activation in long-term memory and is needed for ongoing processing. However, activated features from long-term memory are susceptible to time-based decay and similarity-based interference. Consolidation of the information is therefore important in limiting decay and similarity-based interference. Poorly consolidated information can become inactive in seconds, whereas items that have been well-consolidated can be preserved for longer. At the heart of this approach is the domain-general capacity limited focus of attention which is a limited resource. The focus of attention is controlled by both voluntary processes (a central executive system) and involuntary processes (orienting system). At times, these processes are in conflict. For example, when you are thinking about the route from your home to the local supermarket (which is activating voluntary processes), you then may hear your favourite song come on the radio whilst thinking of this route (which activates involuntary processes), which causes you to orient your attention towards the radio which can disrupt the focus of attention.

2.2.1.3 The Time-Based Resource-Sharing (TBRS) model

The Time-Based Resource-Sharing (TBRS) model is based on four main assumptions (Barrouillet et al., 2004; Barrouillet et al., 2007; Barrouillet et al., 2011). The first assumption posits that information processing and maintenance utilise the same limited resource. This limited resource involves focusing attention to process external stimuli and focusing attention to maintain items in memory, which has been previously described as voluntary controlled attention (Engle et al., 1999). Second, controlled attention can only focus on processing or maintenance at any one time, given that they both use the same limited resource. Third, at the moment in which the focus of attention is diverted away from the memory items, a time-related decay occurs in which the memory items begin to diminish (Cowan, 1995, 1999; Towse & Hitch, 1995). When further processing of new items requires attention, this time-related decay continues, further affecting the memory items. To keep the previous processed memory items maintained and activated in memory, it is necessary to reactivate them using some form of re-attentional focusing. This can potentially be achieved by two different means: 1) to actively rehearse the previously presented information (Baddeley & Logie, 1999); 2) to engage in rapid and covert retrieval processing (Cowan, 1992; Cowan et al., 1994) with the TBRS model favouring the latter. The fourth assumption is based on a rapid and incessant switch between processing and maintenance. As noted earlier, processing and maintenance rely on the same limited resource and a time-related decay occurs when items are outside the focus of attention; it is therefore imperative that the focus of attention switches between each component to allow for processing of memory items and maintaining previously presented items to minimise time-related decay. It is said that the rapid switching occurs during short periods of time irrespective of how demanding the task is (Barrouillet et al., 2007).

2.2.2 The neural basis of visual working memory

The neural basis of visual working memory has been well investigated since the discovery of neural activation of the pre-frontal cortex (PFC) in humans and non-human primates during the delay period of a working memory task (Courtney et al., 1997; Fuster and Alexander, 1971; Kubota & Niki, 1971). Historically, it was suggested that visual memory is a primary function of the PFC (Goldman & Rosvold, 1970; Levy & Goldman-Rakic, 1999). However, more recent research has found a vast network of both high-level and low-level activations involving the prefrontal (Riley & Constantinidis, 2016), parietal (Xu & Jeong, 2015) and sensory cortices (Serences, 2016). Crucially, these brain regions do not work discretely, rather they rely on interplay between them (for review, see Christophel et al., 2017). For example, Gazzaley and Nobre (2012) concluded from a range of human neurophysiological studies that stimulus-selective sensory cortices (such as the early visual areas) are activated along with the prefrontal and parietal regions in working memory tasks.

Interestingly, neuropsychological studies show how different brain regions may interact during visual working memory tasks and demonstrate how specific brain regions have primary functions (for review, see Xu, 2017). Collectively, evidence suggests that the PFC exerts executive control and may partly store representations in VWM. Furthermore, PFC top-down control over the occipital regions and the posterior parietal cortex (PPC) ensures that visual representations are property encoded and then transferred from the visual cortex to the PPC where information is then stored. In addition, during the delay period of a VWM task, top-down control on the visual cortex enables the comparison between the visual representation and the test array presentation. In this description of the neural basis of VWM, the primary function of the visual cortex is encoding, whereas storage relies on the PPC and the primary role of the PFC is top-down control, but may also be involved in VWM storage (Xu, 2017). In support of this view, research has found that the PFC is involved in the online control of storage rather than storage per se (Berryhill, 2012; D'Esposito & Postle, 2015; Smith & Jonides, 1999). In addition, the PPC plays an important role in VWM storage (Berryhill, 2012; Ester et al., 2015; Sprague et al., 2014, 2016; Xu & Chun 2006), with fMRI studies showing successful classifier decoding of visual features such as spatial information and colour in the PPC (Ester et al., 2015; Sprague et al., 2014, 2016). This interpretation is also in keeping with that of the MCM of visual memory, in that the visual buffer is used to generate and encode information and is situated in the visual cortex, while the storage of information takes place in the visual cache which is proposed to be situated in the PPC (Todd & Marois, 2005; Borst, Niven & Logie, 2012).

The aforementioned description may however oversimplify the distinction in functionality between brain regions. Research has proposed that the early visual cortex is not only involved in encoding of visual information but might also play a primary role in the information storage (Postle, 2015; Pasternak & Greenlee, 2005; Serences, 2016). Support for this proposal has been gaining traction recently as fMRI-MPVA studies have shown that visual features can be decoded in early visual areas during the delay period in a VWM task (Albers et al., 2013; Serences et al., 2009; Tong & Harrison, 2009) which has been found to be a robust finding in the literature (Bettencourt & Xu, 2016; Ester et al., 2015). The storage aspect of the early visual cortex is further supported by transcranial magnetic stimulation (TMS) studies which show that applying TMS to the early visual areas significantly impairs encoding and storage in a VWM task (van de Ven et al., 2012). Other researchers have found strong positive correlations between the PPC and the early visual areas activity, and working memory capacity, further strengthening the idea that the early visual areas are involved in storage of the visual information (Todd & Marois, 2005). Indeed, the sensory recruitment model of VWM proposes that the same sensory systems involved during encoding also support maintenance and retrieval of information in working memory (Cattaneo et al., 2009; Postle, 2016).

2.2.3 Measuring Visual memory in the short-term

There is a broad array of tasks measuring visual memory in the short-term (for review, see Pearson et al., 2013; also see, Wilhelm et al., 2013 for measuring working memory). Some of the most commonly used measures are simple and complex span tasks (for review, see Aben et al., 2012). Simple span tasks tap processes that are associated with storage of information, whereas complex span tasks engage both the storage and manipulation of information. An example of a visual simple span task is the Corsi block task (Corsi, 1972). This task is used to investigate participants' ability to maintain visuospatial information. Participants are shown 9 blocks on a screen, then single blocks sequentially change colour. The task requires participants to reproduce the block sequence order. Performance is measured by both the longest sequence that can be remembered, known as the Corsi span (capacity) and the total number of correct sequences. In addition to information storage, complex span tasks such as *n*-back measures maintenance and manipulation of visuospatial information (Kirchner, 1958). In the *n*-back task, participants are required to maintain a sequence of squares in a grid and must continually monitor and update the sequentially presented visual stimuli. Participants are instructed to determine whether each square is in the same position as it was at *n* (2, 3 and 4) positions back (e.g., a 2-*n* back would mean detecting if a square appears in the same position with a single presentation in-between). Performance is typically measured by *d*' or error rate and response time.

Visual change detection tasks are the most common methods used to provide capacity estimates of visual working memory (Cowan et al., 2006; Luck & Vogel, 1997, 2013; Wheeler & Treisman, 2002). A typical visual change detection task contains a sample array, an interval and a test array. The sample array consists of a number of visual stimuli that is to be remembered, the stimuli then disappear, and after a short interval, the test array is presented with either exactly the same stimuli, or with one different stimulus (e.g., location or colour). The aim of the task is for participants to detect whether a change has occurred by responding with either "same" or "different" (Figure 2.7). Figure 2.7 on the left represents sequential presentation of stimuli (Bharti et al., 2020) and, on the right, simultaneous presentation of stimuli, which is one of the popular versions of the change detection task (Luck & Vogel, 1997; Phillips, 1974; Wheeler & Treisman, 2002). When all items are presented at test, this is called full display design, whereas, when a single item is presented at test, this is called a single-cue design (Figure 2.7). The typical finding is that increasing the number of items during the sample array reduces performance at test (Luck & Vogel, 1997, 2013).

Other change detection paradigms, such as the method of adjustment, have been used to provide capacity estimates of VMst by measuring precision of objects in the mind (Bays & Husain, 2008). Similar to the commonly used visual change detection task, participants are briefly presented with a visual array (e.g., several bars that differ in colour). After a short delay, participants are cued to reproduce one of the features from the previous display items by using a method of adjustment (e.g., indicate the exact colour of the bar that was previously presented at the cued location using a colour wheel). Similar to the typical visual change detection task, increasing items at the sample display reduces precision at test (Bays et al., 2009; Bays & Husain, 2008).

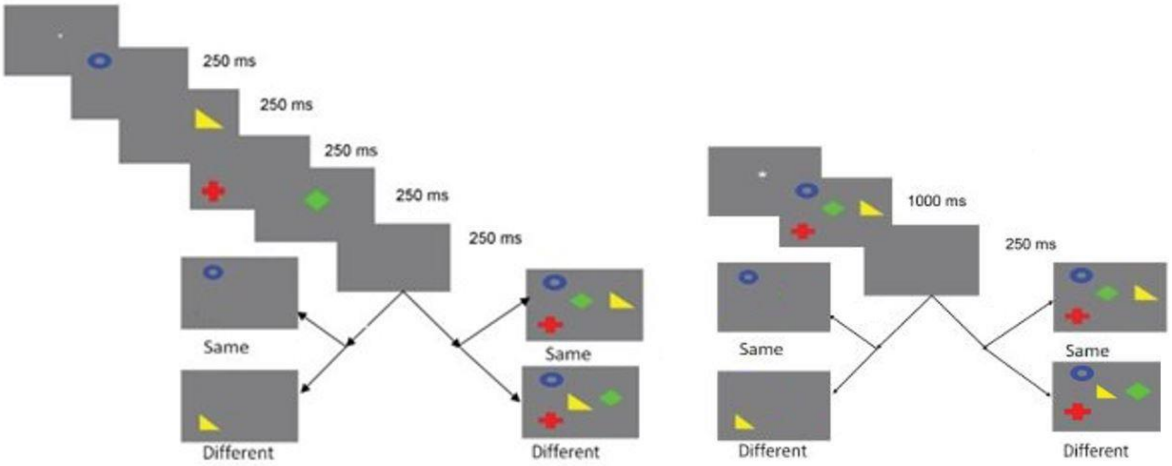

Figure 2.7. Sequential and simultaneous change detection tasks. Left: sequential presentation with a single cue test array (left) and a whole display test array (right). Right: simultaneous presentation with a single cue test array (left) and whole display test array (right). Example test displays show ‘same’ and ‘different’ trials for each change detection task.

2.2.4 Capacity Limitations of visual memory in the short-term

Visual memory in the short-term is severely capacity limited to ~4 items (Cowan, 2001; Luck & Vogel, 1997; Zhang, & Luck, 2008). However, individual differences in working memory capacity demonstrate how variable the capacity limit is (Conway et al., 2007). The importance of higher working memory capacity is far-reaching as it has been found to predict important personal skills and achievements. For example, people with higher capacities tend to be better at multitasking, reading and listening comprehension, vocabulary learning, and following directions (Engle, 2002). Moreover, higher educational achievement and fluid intelligence are associated with higher working memory capacity (Ackerman et al., 2005; Conway et al., 2003; Engle, 2002).

The major consensus is that VMst is capacity limited. However, questions remain as to how these limits arise (for review, see Oberauer et al., 2016). Two of the main theories to account for the capacity of visual memory are slot-based models (e.g., Awh et al., 2007; Cowan, 2001; Luck & Vogel, 1997) and resource-based models (e.g., Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Franconeri et al., 2013; Wilken & Ma, 2004; see van den Berg et al., 2014 for comparison between models). The former depicts that there is a definite number of objects that can be remembered; any number below this threshold can be remembered, whereas any number above this cannot be remembered. For example, if you have a fixed limit of 4 and are presented with 5 objects, you would be able to hold four of them, but completely neglect any encoding of the 5th object. In addition, item-based models propose that features (i.e., colour and shape) can be integrated into an object at no extra cost. Luck and Vogel (1997) showed in a series of change detection tasks that VMst capacity remains consistent (~4 objects) irrespective of either longer encoding times or whether an object contains multiple task relevant features. These results point towards the capacity of VMst being conceptualised as integrated objects rather than individual features. objects.

Alternatively, flexible models propose that VMst capacity is a resource that can be distributed across objects, but each object will be represented less well with every addition to set-size. Resource-based models propose that increasing complexity by adding featural properties (i.e., colour and shape) reduces the resolution of storage or leads to partial storage of the object.

Bays and Husain (2008) used a method of adjustment paradigm to investigate the precision with which a VWM array can be remembered. They found that precision is dependent upon the number of items presented. These findings illustrate that a limited resource is allocated across items that deplete with increasing items presented. In contrast to the slot-based model, these findings suggest that the capacity of VMst should be conceptualised as individual features rather than integrated objects.

Others suggest that capacity limitations are due to interactions between representations that cause interference (Farrell & Lewandowsky, 2002; Lewandowsky & Oberauer, 2009; Oberauer & Kliegl, 2006; Oberauer & Lewandowsky, 2008). Interestingly, interference-based accounts can mimic data patterns that have been attributed to slot-based and resource-based models, suggesting that both slot-based and resource-based models could be explained by inter-item interference (Endress & Szabó, 2017). Other models explain capacity limitations in VMst as being due to temporal constraints on processing and storage (Barrouillet et al., 2011; for review of decay theories, see Ricker et al., 2016). For example, Quirk et al. (2020) used a change detection style task to investigate if longer encoding time improved visual working memory capacity. They found a significant improvement in capacity when objects were presented for 1000ms in comparison to 200ms (others have found similar results, see Li et al., 2020). This finding suggests that VMst capacity is not solely dependent upon either a fixed capacity or a flexible resource, instead capacity varies as a function of encoding duration.

Real-world objects have been found to increase visual working memory capacity compared to simple stimuli (Brady et al., 2016). The improvement in capacity for real-world objects is thought to be due to activations of episodic visual long-term memory which supports memory perfromance in the short-term (Cowan, 2001; Lin & Luck, 2012). Alternativley, Li et al. (2020) found that real-world objects did not improve capacity estimates; rather, capacity estimates were similar for real-world and simple stimuli. This finding suggests that conceptual information does not improve capacity of VMst.

The way in which the information is presented and organised has a direct effect on VMst capacity (Jiang et al., 2000; Lecerf & De Ribaupierre, 2005, for review, see Luck, 2008). The results from behavioural studies tentatively showed equivocal results between simultaneous and sequential presentation of visual information, with the former presenting a slight superiority (e.g., Bharti et al., 2020). However, limited studies provided estimates of capacity for the two modes of presenation. One study that provided estimates of VMst capacity investigated how encoding of simultaneous and sequential visual working memory arrays alters performance in a series of different test arrays (Blalock & Clegg, 2010). Participants were presented with simultaneous and sequential sample arrays and were tested under 4 spatial configuration conditions: no change (same items in the same location), new configuration (entirely new array), array shift (items have the same spatial organisation but the absolute position of the array has moved) and item switch (two items exchange places in the spatial organisation). They found that capacity was higher in the simultaneous presentation than the sequential presentation in all four conditions. These findings illustrate that simultaneous encoding of visual information can influence memory capacity and potentially uses configural encoding, which supports the *relational encoding hypothesis* (Blalock & Clegg, 2010; Jiang et al., 2000). The relational hypotheses states that presented items are inter-related and encoded together (Alvarez, 2011; Brady & Alvarez, 2011). Alternatively, others have found that performance improves in the sequential presentation in comparison to the simultaneous condition (Emrich & Ferber, 2012; Fougnie & Marois, 2009; Ihssen et al., 2010; Yamamoto & Shelton, 2009). These findings suggest that sequential presentation involves independent encoding of each item. The *independent encoding hypothesis* states that individual items are encoded separately, and items are not interdependent (Woodman et al., 2012), as opposed to the *relational encoding hypothesis* (Alvarez, 2011; Brady & Alvarez, 2011). Encoding items sequentially improves performance as compared to simultaneous mode of presentation, because sequential encoding allows for the focusing of attention at a specific location (Yamamoto & Shelton, 2009), less item confusion (Frick, 1985) and less competition between stimuli (Desimone & Duncan, 1995; Kastner, De Weerd, Desimone, Underleider, 1998; Kastner, De Weerd, Pinsk et al., 2001).

Chapter 3: The relation between visual imagery and visual perception and visual imagery and visual short-term memory

3.1 Visual Imagery and visual perception

3.1.1 Neural evidence

Substantial evidence has been found for neural overlap between perception and imagery (for review, see Dijkstra et al., 2019). It is well established that there is overlap in activation in the visual cortex between imagery and visual perception (Klein et al., 2004; Pearson, 2019; Pearson et al., 2015; Slotnick et al., 2005). For example, low-level activity was shown to be retinotopically organised (e.g., vertical/horizontal stimuli) with imagery representing low-level features in the visual cortex, thus suggesting that imagery and visual perception share low-level anatomical substrate (Klein et al., 2004; Slotnick et al., 2005). Low-level overlap between imagery and visual perception was also found to be more pronounced in retinotopic visual areas when individuals report greater imagery vividness (Cui et al., 2007). Furthermore, perception encoding computer models are able to successfully identify low-level features of imagined scenes (Naselaris et al., 2015). These findings provide evidence for a set of shared processing resources between imagery and visual perception.

Similarities between visual perception and visual imagery go beyond the early visual areas recruitment with evidence showing considerable overlap in higher visual areas (Dijkstra et al., 2019; Reddy et al., 2010). Johnson and Johnson (2014) used scenes and found that throughout the ventral stream imagery partially re-instated the same patterns of neural activity that was experienced during perception. Notably, using MVPA, a classifier was less able to distinguish between perception and imagery at higher levels, such as the retrosplenial cortex, than at lower visual areas, such as the occipital place area. This suggests that at higher levels of scene processing there is more abstraction, meaning that activation here is more similar to that activated during imagery. Similarly, Lee et al. (2012) showed similarities in the activation at all areas of the ventral stream in imagery and perception for objects. In particular, they showed that activation patterns could be used to decode which object was being both perceived and imagined (from a set of 10), albeit with weaker decoding for imagery. There were however clear differences in activation patterns in imagery and perception, potentially reflecting different network dynamics. This interpretation is consistent with the findings of Dijkstra et al. (2017) who used dynamic causal modelling (DCM) and found differences in connectivity between fronto-parietal and visual regions for visual perception and visual imagery. The findings suggest that visual perception utilises both bottom-up and top-down processing for visual experience, whereas bottom-up processing is absent for visual imagery. Instead, a greater increase in effective connectivity was found from top-down activations to lower visual areas in visual imagery, suggesting that extra processing resources are needed to enhance the visual representation in comparison to visual perception. This top-down connection has been found to be important for many cognitive processes such as VWM (Gazzaley & Nobre, 2012), selective attention during encoding (Mayer et al., 2007; Zanto et al., 2011) and the maintenance of visual representations (Higo et al., 2011; Nobre et al., 2004).

Similar neural representations have been found in the parietal cortex for visual perception and visual imagery (Dijkstra et al., 2017). The parietal cortex was shown to be a relevant cortical structure for visual perception, in particular, its role in spatial and feature-based attention (Malhotra et al., 2009). Similar findings were reported during visual imagery with increased activation in the intraparietal sulcus when focusing on features of an imagined stimulus in comparison to a perceptual stimulus (Ishai et al., 2002). Furthermore, a co-ordinate-based meta-analysis found strong activations in the parietal lobe during spatial comparisons in imagery (Winlove et al, 2018). The parietal cortex is also said to be responsible for encoding the saliency of the visual features in visual perception, visual imagery and VWM, which is then used for later top-down processing (Bogler et al., 2011; Yun et al., 2013). However, the role of top-down connections from the parietal cortex is less clear. Dijkstra, et al. (2017) found that during visual perception inhibition increases between the intraparietal sulcus (IPS) and the early occipital areas, whereas with more vivid imagery this connection produces a decrease in inhibitory influence. It has been suggested that the interplay between these regions for visual perception is indicative of the predictive encoding view that enables an accurate representation of the outside world (Den Ouden et al., 2012; Friston, 2005; Rao & Ballard, 1999). In contrast, the inhibitory coupling between the IPS and early occipital areas for imagery is suggestive of an imagery-specific mechanism that attempts to maintain an image in the early visual areas (Dijkstra et al, 2017).

The frontal cortex is activated for both visual imagery and visual perception when directing selective attention to locations (Ishai et al., 2000; Nobre et al., 2000). Nobre et al. (2004) used fMRI to investigate the neural systems underlining directing attention to locations in an imagined and perceived image. Critically, extensive overlap was found in several frontal regions. Interestingly, the pattern of activation is similar to activations found in working memory, long-term memory and tasks that involved executive processes (D’Esposito et al., 2000; Haxby et al., 2000; Ranganath et al., 2003). Although there was extensive similar neural activation between visual imagery and visual perception, this overlap was not identical. Orienting attention to an internal representation in comparison to orienting attention to the external world involved higher anterior prefrontal activation, suggesting that this region might be involved in the specific act of zooming or shifting spatial attention (Nobre et al., 2004). These findings illustrate that the neural basis of visual imagery and visual perception are similar when orienting selective attention to the internal and external world, but different regions become selectively engaged during the act of imagining and perceiving.

Evidence indicates that the decoding of representations in the frontal cortex is less clear during visual imagery than visual perception. Stimulus identity has been successfully decoded in the frontal cortex during visual perception tasks (Chan, 2013; Hebart et al., 2018). For example, Jiang et al. (2007) used fMRI-rapid adaptation paradigm that was used to measure brain activity before and after categorising training. The lateral PFC was found to be sensitive to changes in category membership after training. Moreover, training improved discrimination performance on stimuli that were selected for training. In contrast, decoding stimulus identity in this region during visual imagery task has been less successful (Ishai et al., 2000) and this region is thought to be more involved in the top-down control of images rather than the content (Mechelli et al., 2004). Indeed, decoding studies showed higher accuracy when decoding task identity rather than stimulus identity in both imagery and visual perception (Bugatus et al., 2017; Hebart et al., 2018). This suggests that the frontal cortex is more involved in task-relevant structure rather than stimulus content and saliency for both visual imagery and visual perception (Dijkstra et al., 2019).

3.1.2 Behavioural evidence

Behavioural research investigating the relationship between visual imagery and visual perception has shown that visual imagery can have a functional effect on visual perception (Pearson et al., 2015). For example, Pearson et al. (2008) showed that imagining or perceiving oriented lines biased future perception. Similar functional effects have been found when investigating colour. Specifically, Chang et al. (2013) found that perceptual dominance was biased when participants were imagining colours. Furthermore, weak perceptual stimuli showed similar effect to visual imagery, such that perceptual dominance was also biased by weak perceptual stimuli. Others have shown that motion imagery can have a functional effect on subsequent motion perception and imagining orientated lines can induce an orientation after effect on a subsequent perceptual stimulus (Chang & Pearson, 2018; Linder et al., 2011). Taken together, these findings suggest that visual imagery works much like visual perception.

There is also considerable evidence that visual imagery can have a facilitatory effect on visual perception (Chang et al., 2013; Keogh & Pearson, 2011; 2014; Pearson, 2014; Pearson et al., 2008; Pearson et al., 2011; Sherwood & Pearson, 2010). For example, Ishai and Sagi (1995) found that imagery interacts with visual perception, such that imagining visual patterns with a concurrent and congruent visual percept boosts sensory performance in a detection task. One of the most popular paradigms used to measure the impact of imagery on subsequent perception is that of binocular rivalry. Representations in imagination bias perception in the subsequent rivalry task, with the degree of dominance serving as a marker of sensory strength of the imagery. The general finding is that imagining one of two stimuli increases the probability of seeing the stimulus in the subsequent binocular rivalry presenation (Chang et al., 2013; Keogh & Pearson, 2011; 2014; Pearson, 2014; Pearson et al., 2008; Pearson et al., 2011; Sherwood & Pearson, 2010). In addition, Pearson et al. (2008) found that the facilitation effect endures over time even when imagery and perception are separated by a demanding task. Furthermore, imagery priming was stronger in a subsequent perceptual rivalry task at longer durations. However, the facilitation effect can also be reduced when generating an object in the presence of background luminance (Chang et al., 2013), suggesting that luminance can disrupt imagery generation. Similar to imagery, substantial evidence shows that weak perception facilitates subsequent perception (Brascamp et al., 2007; Chang et al., 2013; Tanaka & Sagi, 1998). Thus, evidence suggests that both weakened perceptual stimuli and imagery have a similar faciliatory effect on subsequent perception (Pearson, 2019). However, to date, only a strong visual percept (i.e., high contrast) has been shown to have a suppressive effect on subsequent perceptual tasks (for review, see Pearson, 2014). In contrast, imagery has not been shown to have a suppressive effect on subsequent perception (Pearson et al., 2015). The evidence therefore suggests that the influence of visual imagery and visual perception on subsequent perception is partly dependent upon the visual strength/energy of the prior stimulus.

3.2 The relation between visual imagery and visual memory

3.2.1 Neural evidence

Visual imagery appears to be very similar to VWM in that both require active representation and manipulation of visual information. Although working memory is typically thought of as maintenance and manipulation of recent perceptual input it is well documented that visual imagery is used as a strategy during VWM and is incorporated in working memory models (Baddeley & Hitch, 1974; Logie, 1995, 2003, 2011). However, it is interesting that given the similarities between imagery and VWM, limited neuroimaging research has actively attempted to differentiate imagery and VWM with the two often investigated in separate literatures (Tong, 2013).

In terms of neural activation, imagery and VWM have been shown to be similarly associated with activity in the lower and higher visual areas (Harrison & Tong, 2009; Kosslyn, Ganis, & Thompson, 2001; Kosslyn & Thompson, 2003; Kosslyn et al., 1995). Studies using transcranial magnetic stimulation (TMS) have found that disrupting the early visual areas impairs performance in both imagery and VWM tasks (Cattaneo et al., 2011; van de Ven & Sack, 2013). This suggests that imagery and VWM utilise the early visual areas when encoding and storing visual information. Moreover, similar patterns of activations were found in visual areas for imagery and VWM (Albers et al., 2013; Lee et al., 2012; Reddy et al., 2010). Albers et al. (2013) used a MVPA approach with fMRI to compare activity in the early visual areas (V1-V3) between imagery and VWM. A decoder predicted which of the three oriented gratings were being held in imagery or VWM, even when the content was trained on the other process decoder, suggesting a shared common representation between imagery and VWM. However, the generalisation was not perfect, potentially because internally generated images are more variable. These findings suggest that imagery and VWM are highly similar but are not identical.

The decoding of imagery and VWM content in the visual areas support sensory-recruitment models of working memory (Awh & Jonides, 2001; Postle, 2006; D'Esposito, 2007; Scimeca et al., 2018) Sensory-recruitment models propose that the same sensory regions (i.e., early visual areas such as areas V1 and V2) are activated during visual perception and VWM with the content of memory being maintained in the sensory regions, while activation in high-level areas (i.e., fronto-parietal regions) are task-related non-content memory processes. In line with this view, evidence suggests that high-level areas are related to top-down control of visual information and task goals, rather than content specific information in both imagery and VWM (Ishai et al., 2000; Mechelli et al., 2004; Riggall & Postle, 2012). Taken together, this evidence suggests that the high-level areas are used in VI and VWM to support task relevant structure of stimuli and top-down control of visual information rather than the specific content.

However, previous findings also suggest that content-specific information is represented in both visual areas and high-level areas in imagery and VWM (Bettencourt & Xu, 2016; Christophel et al., 2017; Dijkstra et al., 2017; Ester et al., 2015; Schlegel et al., 2013; Ragni et al., 2020). For example, Ragni et al. (2020) investigated the content of visual imagery using a MVPA with fMRI. Participants were instructed to imagine specific information (e.g., objects and letters) in a spatial judgement task. Searchlight-based MVPA found that the type of information being imagined could be decoded in early visual areas, parietal regions, and prefrontal regions. Similarly, in a VWM study, Ester et al. (2015) were able to reconstruct VWM representations based on activity patterns in the visual cortex, parietal, and frontal cortex. These findings suggest that content of imagined and remembered information is represented in sensory regions as well as non-sensory regions, and that the visual areas, parietal and frontal regions are important for the encoding and maintenance of visual information.

Collectively evidence suggests overlap in the parietal cortex between VWM and imagery (Albers et al., 2013; Pearson et al., 2015). Critically, in VWM, the parietal cortex has been found to be an important structure for VWM storage (Berryhill, 2012; Sprague et al., 2014; 2016; Xu & Chun, 2006). For example, Todd and Marois (2004) used fMRI coupled with a capacity estimate memory task and found that activation in the posterior parietal cortex (PPC) was related to short-term memory capacity. The fMRI activation increased in the intraparietal sulci up to set-size 4 and then levelled off. This capacity estimate is aligned with the typical capacity estimate found in behavioural short-term memory studies of approximately 4 items (Cowan, 2001; Luck & Vogel, 1997; Zhang, & Luck, 2008). This suggests that the PPC is a key neural structure for short-term memory capacity. Furthermore, the PPC is thought to be the neural architecture of the visual cache (Borst, Niven & Logie, 2012; Todd & Marois, 2005), which has been argued to store a small number of visual objects in both imagery and memory in the short-term (Borst, Niven & Logie, 2012). Taken together, these findings suggest that imagery and short-term memory share PPC neural substrate and might therefore have similar capacity limitations.

Additionally, the number of items held in memory in the short-term is associated with activation in the occipital cortex (Riggall & Postle 2012; Emrich et al., 2013; Ester et al., 2013; Todd & Marois, 2004; 2005). For example, Todd and Marois (2005) used voxel-wise individual differences analysis and found that the superior occipital cortex activity partly predicts individual differences in short-term memory storage. This work suggests that the superior occipital cortex is not a generic component of short-term memory capacity, but instead individual capacity limits could be set in the superior occipital cortex. Individual differences in memory in short-term capacity have also been found in the primary visual cortex (Bergmann et al., 2014). Bergmann et al. (2014) found that the size of V1 predicted the number of items that can be maintained in short-term memory, with individuals with larger V1 tending to have increased capacity. Interestingly, Bergmann et al. (2016) investigated visual imagery using the binocular rivalry paradigm and matched this measure with fMRI retinotopic mapping of the early visual cortex. They found a negative relationship between the size of V1 and imagery strength, but a positive relationship between V1 and imagery precision. In other words, the individuals with a larger V1 tend to have weaker imagery strength, but more precise visual imagery. Taken together, this evidence suggests that the occipital cortex, particularly the early visual area of V1 is not only involved in encoding of visual information but is important for memory in the short-term capacity, and potentially, for visual imagery capacity.

3.2.2 Behavioural evidence

It has proven difficult to establish if imagery and VWM are one and the same partly due to the differences in behavioural tasks and measures (Pearson, et al., 2015). However, behavioural work has begun to investigate the relationship between imagery and VWM. For example, Keogh and Pearson (2011) found that VWM performance can be predicted by the strength of a mental image. However, this effect was attenuated when imagining an object in the presence of background luminance for participants who were good imaginers. On the other hand, those participants who were poor imaginers still performed well on the task when the background luminance was presented, which suggests that these participants were using an alternative non-visual strategy (e.g., a linguistic strategy) to perform the task (Pylyshyn, 2003). Developing this further, Keogh and Pearson (2014) showed that the strength of an individual’s imagery could predict working memory capacity. These results help to explain that the large individual differences found in VWM performance and capacity could be due to the strategy used to perform the task (Pearson & Keogh, 2019). It could be that individuals with strong mental imagery use visual strategies to perform a task, whereas those with weaker imagery rely more on non-visual strategies.

Behavioural studies appear to indicate both similarities and differences between visual imagery and visual memory. Substantial overlap has been found between visual imagery and visual working memory in performance related tasks with visual interference (e.g., visual noise, uniform background luminance, and irrelevant pictures) attenuating performance in imagery and VWM tasks (Baddeley & Andrade, 2000; Darling et al., 2009; Dean et al., 2005; 2008; Keogh & Pearson, 2011, 2014; McConnell & Quinn, 2004; Sherwood & Pearson, 2010; Valenti & Galera, 2020; Vasques et al., 2016). For example, Borst, Ganis et al. (2012) asked participants to judge the featural properties (e.g., diagonal lines) of letters by retaining (self-generated) mental images or by being shown letters (VWM task). In a series of conditions participants were presented with unstructured dynamic visual noise, structured dynamic visual noise (contained structural properties of the to-be-imagined or to-be-remembered letters) and no visual noise. It was found that participants made more errors in the structured dynamic visual noise condition than in the unstructured dynamic visual noise condition in both imagery and VWM. This suggests that imagery and VWM share a common mechanism and share the same depictive format which is sensitive to structural visual interference. However, Borst, Ganis et al. (2012) surprisingly found that the unstructured dynamic visual noise condition affected the VWM task and not the imagery task, suggesting that the processes are not identical.

Indeed, other studies have found differences between imagery and VWM when presenting interference (Andrade et al., 2002; Avon & Sesterveri, 2005; Borst, Niven and Logie, 2012; Van Der Meulen et al., 2009; Zimmer & Speiser, 2002). For example, Van Der Meulen et al. (2009) found that imagery and VWM were sensitive to different types of interference. VWM retention was affected by spatial tapping but not by irrelevant pictures. In contrast, imagery *generation* was affected by irrelevant pictures, but was not affected by spatial tapping. The double dissociation suggests that the process underlying imagery generation is separate to that of short-term visual retention. It is possible that visual imagery activates an active visual representation store, likened to an imagery buffer, whereas the retention of visual stimuli in visual short-term memory is maintained in a passive store (Andrade et al., 2002; Cornoldi & Vecchi, 2003; Pearson, 2001; Quinn & McConnell, 2006). Indeed, irrelevant visual input has been found to disrupt image generation but does not disrupt image retention (Borst, Niven & Logie, 2012). It could be that imagery and VWM information are stored in the same temporary retention store. However, this store is not involved in imagery generation. These findings are in alignment with Logie's (1995, 2003, 2011) workspace model which proposes separate active and passive visual stores when representing visual information. Collectively, these findings are consistent with the idea that imagery and VWM processes might be related, in that they share the same visual retention store. However, they seem to be separable, such that imagery generation potentially uses a separate visual buffer or store to VWM.

Another interpretation is that irrelevant visual interference affects imagery generation by reducing imagery vividness (Andrade et al., 2002; Baddeley & Andrade, 2000). In this instance, the subjective experience of images is reduced without disrupting the storage component per se. On the other hand, VWM vividness is not disrupted by irrelevant visual interference because task relevant visual information is perceived via low-level visual input. It could be that visual interference affects imagery vividness by reducing the quality of the underlying visual representation, which in turn affects task performance.

In contrast, the contradictory findings between imagery and VWM in the presence of interference could be due to task difficulty and stimulus complexity (Andrade et al., 2002; Borst, Niven & Logie, 2012; Vasques et al., 2016). In these studies, participants retained highly detailed visual information which potentially requires continual rehearsal of the information. In line with this view, the active rehearsal of the detailed visual information might require the active visual buffer rather than the passive visual cache (Darling et al., 2009; Kosslyn & Thompson, 2003). In contrast, studies that did not find an effect of irrelevant visual interference on retention could be due to the use of stimuli that require less precision. For example, Van Der Meulen et al. (2009) found that VWM performance was unaffected by irrelevant pictures. However, they only asked participants to remember simple properties of the letters (e.g., letter case) in their VWM task. It is possible that the use of simple stimuli allowed participants to use the visual cache which is less affected by visual interference in comparison to that of the visual buffer. In sum, substantial evidence suggests that imagery and VWM are related. However, significant uncertainty exists as to whether they are one and the same.

Chapter 4: Capacity models of visual memory in the short-term

4.1 Introduction

As previously discussed in the chapter on capacity limitations in visual memory in the short-term (see section 2.2.4), estimating capacity of memory broadly falls into two categories: item-based models (Cowan, 2001; Luck & Vogel, 1997) and resource-based models (Alvarez & Cavanagh, 2004; Bays & Husain, 2008). In summary, the former assert there is a definite number below which objects can be remembered and then above which no more objects can be remembered. On the other hand, flexible models posit that we can remember as many objects as we intend, but each object will be remembered less well with every addition to set-size. In addition, item-based models propose that features (i.e., colour and shape) can be integrated into an object at no extra cost. Instead, resource-based models propose that increasing complexity, by adding featural properties, reduces the resolution of storage or leads to partial storage of the object.

Change detection tasks are the most common methods used to provide capacity estimates of VMst. As previously mentioned, the typical change detection task contains a sample array, an interval, and a test array: the sample array consists of a number of stimuli to be remembered, the stimuli then disappear and, after a short interval, the test array is presented with either exactly the same stimuli, or with one different stimulus. The aim of the task is for participants to detect whether a change has occurred by responding with either “same” or “different” (Figure 2.7). Figure 2.7 represents sequential presentation of stimuli (Bharti et al., 2020) and simultaneous presentation of stimuli, that is one of the popular versions of the change detection task (Luck & Vogel, 1997; Phillips, 1974; Wheeler & Treisman, 2002).

When all items are presented at test, this is called full display design. In contrast, when a single item is presented at test, this is called a single-cue design (Figure 2.7). The critical difference between the two paradigms is that in the single-cue design participants know which item has changed at test, if any. Whereas in the whole display design, any of the items could have changed at test, if any. Due to this critical difference, the whole display design and the single-cue design have specific formulas for modelling estimates of capacity in change detection. The whole-display formula was formalised by Pashler (1988) and the single-cue by Cowan (2001). Although the formulas are slightly different, both of these models are item-based and have been widely used in measuring memory capacity (Morey & Morey, 2011).

4.1.1 Pashler's formula

The aim of the whole display formula is to estimate how many items can be maintained in memory (Pashler, 1988). The model is based on the assumption that memory has a fixed number of slots. For example, if *N is* > *k* (capacity) then the remaining items *N* above *k* will be discarded and will not be stored in memory. Consider a *change* trial in which an item is different between the sample array and the test array. When *N* items are presented, the participant is only able to encode the number of items that is equal to their *k*. If capacity is greater than the number of items presented, then all items are stored with a probability of 1.0. Therefore, the probability that the change item is in memory is given by *D*:

$$D = \min\left(\frac{k}{N}, 1\right).$$

Here, *k* is capacity, *N* is set-size and min makes sure that the probability does not exceed 1. This instantiation is the storage probability. If the item changed, then the participant detects change with the storage probability. However, if the change is not detected then the participant guesses with probability *G*, which leads to a hit rate given by *H*:

$$H = D + (1 - D)G$$

In this equation, *H* is the hit rate and *G* is the guessing rate. If the display did not change (*same* trial) and the number of items is greater than the participant's capacity, then the participant may be unsure if a change occurred. It could be that no change occurred, or a change occurred in one of the items that was not stored. This leads to the participant to guess *change* with probability *G* (Figure 4.1). Alternatively, if the participant's capacity is greater than the presented items then all items will be stored, and the false alarm rate will be 0. The false alarm probability is given by:

$$F = G'$$

$$G' = \begin{cases} G & k < N \\ 0 & k \geq N \end{cases}$$

The ‘‘effective’’ guessing rate is represented by parameter G'. When k is $< N$, G' equals G, creating uncertainty about whether there was a change. However, when k is > N, the participant will never respond change on a same trial, therefore G' is 0. k and G are given by:

$$\hat{k} = N \left(\frac{\hat{H} - \hat{F}}{1 - \hat{F}} \right) k < N,$$

$$\hat{G} = \hat{F} \quad k < N,$$

In this equation, $\hat{H}$ is the observed hit rate and $\hat{F}$ is the false alarm rate. To obtain good estimates for k and G, it is necessary that $K < N$. If $K \geq N$, then no estimates can be obtained because performance is perfect. Pashler’s model tree can be seen in Figure 4.1.

The Pashler (1988) formula given above is appropriate for whole-display change detection designs but is not suitable for estimating capacity in single-cue designs. This is because in a single-cue design the participant must make a decision about only one item (i.e., has a change occurred in this one item). Whereas, in the whole-display all items are presented in the test array. Therefore, the critical difference is that the participant knows which item is under question.

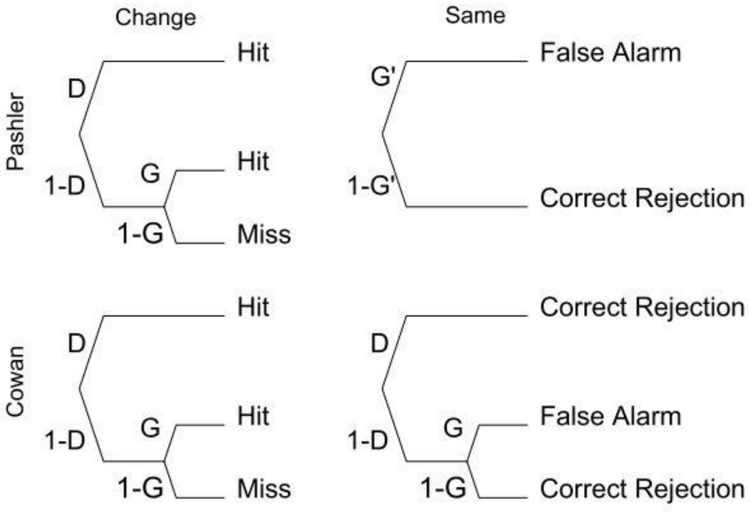

Figure 4.1. Pashler’s (1988) model of whole display change detection performance (top) and Cowan’s (2001) model of single-cue detection performance (bottom). The left and right columns show the trees for change trials and same trials, respectively.

4.1.2 Cowan’s formula

The Cowan (2001) model is appropriate when using a single-cue design. The Cowan (2001) model follows the same formula as Pashler’s (1988) for *change* trials but differs in how *same* trials are modelled (Figure 4.1).

For change trials, the participant identifies change with storage probability $D = \min(K/N, 1)$; or else, the participant guesses. For same trials, the participant responds correctly with storage probability D; or else, the participant guesses. This results into the following hit and false alarm rates:

$$H = D + (1 - D)G$$

$$F = (1 - D)G.$$

Similar to the Pashler (1988) model, if $K < N$, then K and G can be solved to obtain estimates:

$$\hat{k} = N\ (\hat{}H\ -\ \hat{}F)\ k < N$$

$$\hat{G} = \left(\frac{\hat{F}}{1 - \hat{H} + \hat{F}}\right)\ k < N.$$

Again, estimates of capacity can only be obtained when $K < N$. When capacity is greater than the number of items then performance will be perfect.

Both the Pashler (1988) and the Cowan (2001) models are based on the same slot-based fixed capacity model in which items are either encoded or are not encoded into memory. The critical difference between Pashler (1988) and Cowan (2001) models is in how the respective test display items are presented at test. The Pashler (1988) model is based on the whole display design whereby any item could have changed or not changed at test. Here, the participant does not know with certainty which item has changed, or not changed. In contrast, the Cowan (2001) model is based on the single-cue design where a single item could have changed or not changed at test. With this design, the participant knows with certainty which item they should judge as either changed or not changed. Therefore, the formula used to obtain short-term memory capacity is based upon the experimental design (Rouder et al., 2011).

4.1.3 WoMMBAT model

The WoMMBAT (Working Memory Modeling using Bayesian Analysis Techniques; Morey & Morey, 2011) model aims to provide capacity estimates of visual working memory by presenting a Bayesian extension of Pashler (1988) and Cowan's (2001) formulas using the model proposed by Rouder et al. (2008). Rouder et al. (2008) further extends the formulas of Pashler (1988) and Cowan (2001) with the addition of a lapse parameter (Figure 4.2).

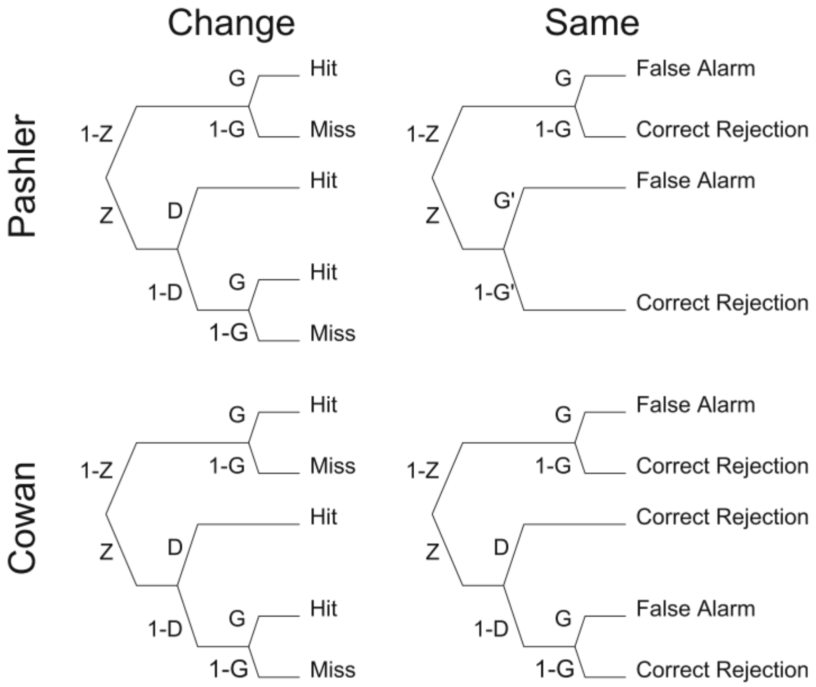

Figure 4.2. Rouder et al.'s (2008) lapse parameter extension of Pashler's (1988; top row) whole display design and Cowan's (2001; bottom row) single-cue design. Left column presents change trials and right column presents same trials.

The attentional lapse parameter accounts for imperfect performance at low set-sizes. This extended model accounts for participants to lapse with a probability of 1 – *Z*, or with a probability of *Z* if successfully attending to the task. Failure to attend to the task will lead to the participant guessing with probability *G* due to the participant having no information about the display. In contrast, the previously defined trees in Figure 4.1 are adopted if the participant successfully attends to the task. The full display design (Pashler) with the addition of the lapse parameter has hit and false alarm rates:

$$H = (1 - Z)G + ZD + Z\,(1 - D)G$$

$$F = (1 - Z)G + ZG',$$

The single-cue design (Cowan) design with the addition of the lapse parameter has a hit and false alarm rates:

$$H = (1 - Z)\,G + ZD + Z\,(1 - D)\,G$$

$$F = (1 - Z)\,G + Z\,(1 - D)\,G.$$

Morey's (2011) WoMMBAT hierarchical model can be seen in Figure 4.3. The first level of the model is the observed data and at the final level is the Bayesian priors. The observed data (hits and false alarms) take the form of binomial distributions:

$$Y_h \ \sim Binomial\left(M_{c\,,}\, P_h\right)$$

$$Y_f \ \sim Binomial\left(M_{s\,,}\, P_f\right)$$

$M_{c\,,}$ represents *change* trials and $M_{s\,,}$ represents *same* trials where P_h and P_f represent the true hit and false alarm rate probabilities. Y_h and Y_f represent the observed hits and false alarm rate probabilities which are distributed as random binomial variables.

The true hit and false alarm rate probabilities are informed by capacity (*K*), attentional lapse (*Z*) and guessing parameter (*G*) which are computed from the multinomial trees and in Figure 4.3. Both *Z* and *G* probabilities are constrained by limits (0,1), however the model transforms these values with a logistic transformation by using the unconstrained parameters *z* and *g* (Figure 4.3):

$$Z = \frac{1}{1 + e^{-z}}$$

$$G = \frac{1}{1 + e^{-g}}.$$

In contrast, a transformation between K and k is made using a Mass-at-chance (MAC) transformation, such that all negative values of k are mapped to $K = 0$.

$$K = \max\ (k, 0).$$

Linear models are then placed on parameters z, g and k (Figure 4.3).

The joint posterior distribution is obtained using a hybrid Markov chain Monte Carlo (MCMC; Liu, 2001) with the prior setting set by the modeler. There are several factors that control the quality of the samples. These are the length of the MCMC chain, the number of burn-in iterations and the MCMC method (*hybrid Monte Carlo*). WoMMBAT uses MCMC chains in order to approximate samples from the joint posterior distribution of each parameter. Samples are continually drawn, and a new sample is approximated using the previous sample, creating a chain of values. The distribution of these samples is a better approximation of the joint posterior as the chain becomes longer. The length of the chain is controlled by the number of iterations. *Burn-in* iterations reject a portion of the samples at the start of the chain to minimise the influence that the first iterations can have on the chain. Finally, the *hybrid Monte Carlo* (Liu, 2001) method simulates the data. The *hybrid Monte Carlo* has two parameters: $\epsilon \ and \ N_{if}$. ε represents epsilon and is an approximation of time. N_{if} represents the number of time simulation steps. The WoMMBAT model has two parameters for ε, a lower and an upper epsilon. The overall goal of the WoMMBAT model is to create good quality MCMC chains (i.e., convergence) in the least amount of time by using the smallest possible values on $\epsilon \ and \ N_{if}$.

In addition, the WoMMBAT model is suggested to be the model of choice as it correctly accounts for weaknesses associated with traditional approaches such as Cowan’s and Pashler’s formulas (Morey & Morey, 2011; Morey, 2011). Notably, it addresses distortions due to non-linearity or meaningless negative capacity estimates (Morey & Morey, 2011). Morey and Morey (2011) account for bias and volatility by placing linear models onto each of the parameters at the second stage of the hierarchical model (Figure 4.3). Meaningless negative capacity estimates are prevalent in Pashler's (1988) formula when false alarm rates exceed hit rates. These negative capacity estimates are undesirable when included in analysis because they produce uninterpretable estimates. Addressing this issue, Morey and Morey (2011) transform capacity using a Mass-at-chance (MAC) transformation. This assigns negative numbers to a single value, for example capacity = 0. This ensures that analysis is not influenced by negative estimates of capacity. These issues are also solved by the hierarchical model as it uses all the data efficiently by integrating all participants and conditions simultaneously. For these reasons, the WoMMBAT model will be used to obtain capacity estimates throughout this thesis.

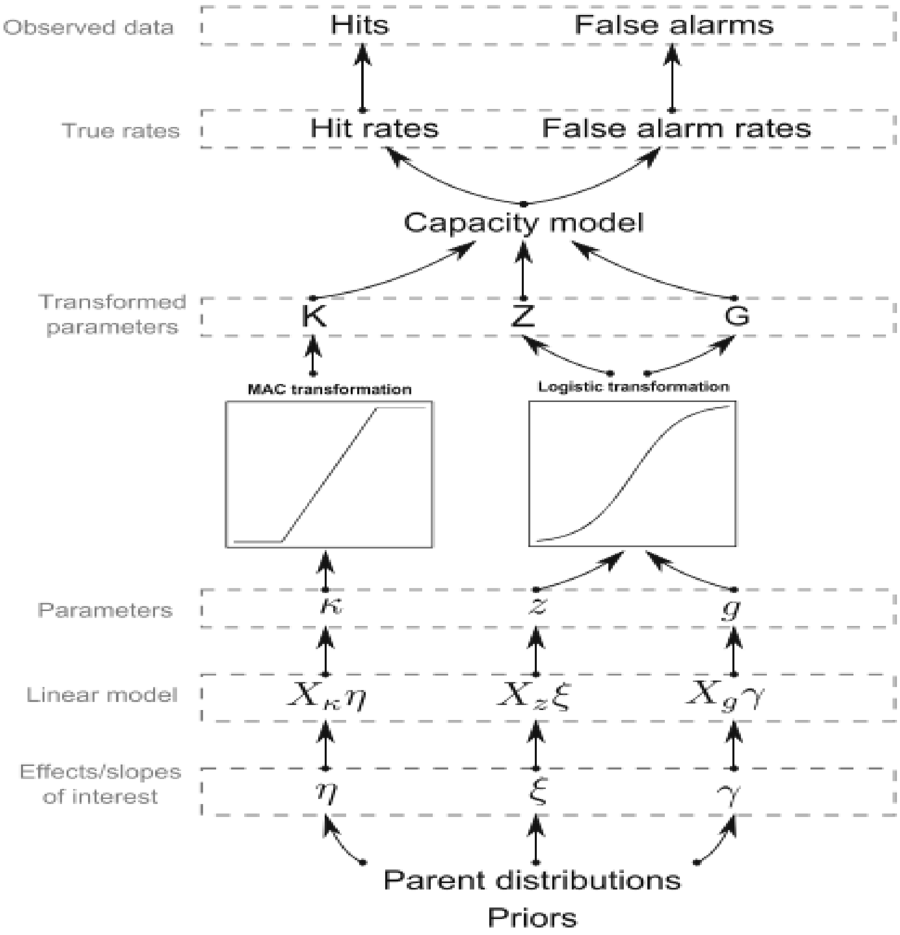

Figure 4.3. Morey’s hierarchical extension model of working memory. At the highest point is the observed data with the Bayesian parent distributions for the priors presented at the bottom of the figure (Morey & Morey, 2011).

Chapter 5: Experiment 1 and Experiment 2

5.1 Introduction

Imagination is a fundamental aspect of cognition, enabling us to traverse time and space and combine information in novel ways. As a central part of everyday experience, it is important to understand the processes that support it. The extent to which visual memory in the short-term, visual imagery and visual perception are distinct, overlapping or involve some common processes is a fundamental question about the nature of visual cognition and has recently become a focus of research (Dijkstra et al., 2019).

Unlike visual perception, visual imagery is a form of visual representation in the absence of current corresponding visual input. This distinction has formed the basis of a debate about whether imagery is depictive and relies upon the same processes as visual perception (Kosslyn et al., 2006) or is based on propositional knowledge of the visual world (Pylyshyn, 2002). To address this issue recent work has explored the extent of overlap in neural activation between perception and imagery at different levels of processing. Typically, these studies involve memorising images that are then either presented again or imagined. This has shown that there is some overlap in activation in the visual cortex during imagery and visual perception (Pearson, 2019). For example, at lower visual areas Klein et al. (2004) found evidence for some retinotopically organised activation for imagined stimuli, with activation clearly differentiated for horizontal and vertical stimuli and closely matching that of perception. Furthermore, these low-level processing similarities are also found in behavioural studies with imagery biasing future perception (Pearson et al., 2008).

Studies using more complex stimuli have also shown considerable overlap between imagery and perception in higher visual areas. Using complex scenes, Johnson and Johnson (2014) showed that throughout the ventral stream imagery partially re-instated the same patterns of neural activity produced during perception. Notably, using multivariate pattern analysis (MVPA) a classifier was less able to distinguish between perception and imagery at higher levels (e.g., the retrosplenial cortex) than at lower visual areas, suggesting that greater abstraction is happening at higher levels, making activation less distinguishable between tasks. Similarly, Lee et al. (2012) found that the content of imagery and visual perception can be decoded from the pattern of activity throughout the ventral stream. However, pattern analysis identified different network dynamics within this pathway for imagery and visual perception. Imagery was found to have an anterior-to-posterior activation along the ventral system, whereas a posterior-to-anterior activation was found for visual perception. This suggests that similar neural substrates are used by both processes, but the way in which the networks work within the substrate are activated differently for imagery and visual perception tasks. This could be driven by the absence of visual input during imagery and the reliance on top-down feedback to posterior brain regions to generate a visual image. In perception, bottom-up input is later modulated by top-down processes whereas bottom-up input is absent in imagery and so early sensory regions receive top-down signals only, with those signals likely much impoverished relative to those elicited by the actual object image. Indeed, this interpretation is supported by Dijkstra et al. (2017) who used dynamic causal modelling (DCM) and found an increase in direct coupling (effective connectivity) activations for visual perception relative to baseline between early occipital cortex (OCC) and the Inferior frontal gyrus (IFG) and between IFG and OCC. This indicates that visual perception utilises both bottom-up and top-down processing for visual experience. In comparison, bottom-up processing was absent for imagery, instead there was more direct coupling between IFG and OCC in imagery than for perception. This increase in top-down activation in imagery is likely driven by the absence of visual input, suggesting that extra processing resources are needed from the IFG to enhance the visual representation in comparison to that of visual perception. This top-down connection has been found to be important for many cognitive processes such as VWM (Gazzaley & Nobre, 2012), selective attention during encoding (Mayer et al., 2007; Zanto et al., 2011) and the maintenance of visual representations (Higo et al., 2011; Nobre et al., 2004). Furthermore, a recent review (Dijkstra et al., 2019) concluded that perception and imagery share a variety of mechanisms throughout the ventral stream from V1 onwards, with greater overlap at higher levels. There is therefore substantial evidence that imagery simulates some characteristics of perception.

Visual imagery is also related to VWM as both require active representation and manipulation of visual information. Working memory involves the activation and manipulation of long-term memories (Baddeley, 2000; Cowan, 2019) and although imagery is similar in this regard, it is also associated with using long term memory to generate novel images (e.g., a pink elephant wearing a top hat reclining on a sun lounger). Yet despite clear similarities, imagery and working memory have tended to be investigated in separate literatures (Tong, 2013).

Behavioural studies exploring the relation between visual imagery and VWM have indicated similarities. For example, visual interference has been found to attenuate performance in both imagery and VWM tasks (Baddeley & Andrade, 2000; Darling et al., 2009; Dean et al., 2005; 2008; Keogh & Pearson, 2011, 2014; McConnell & Quinn, 2004; Sherwood & Pearson, 2010; Valenti & Galera, 2020; Vasques et al., 2016). However, Andrade et al. (2002) found that irrelevant visual input during a VWM task did not affect performance, whereas imagery was affected by irrelevant visual input. One interpretation of these results is that imagery and VWM tap separate underlying processes. Andrade et al. (2002) suggested that the imagery generation activates an active visual representation store, likened to an imagery buffer, whereas the retention of visual stimuli in VWM is maintained in a passive store that is not susceptible to irrelevant visual input. This may be because imagery is a more active process compared to short-term storage (Logie, 1995; Pearson, 2001). For instance, irrelevant visual input interferes with image generation but does not disrupt image retention (Borst, Niven, & Logie, 2012).

In terms of neural activation, both visual imagery and VWM appear to involve lower and higher-level visual areas (Harrison & Tong, 2009; Kosslyn & Thompson, 2003). Studies using transcranial magnetic stimulation (TMS) have found that disrupting early visual areas can impair performance in both imagery and VWM tasks (Cattaneo et al., 2012; van de Ven & Sack, 2013). In an fMRI study, Albers et al. (2013) used MVPA to measure and compare activity in early visual areas (V1-V3) in visual perception, imagery and working memory tasks. A decoder trained on activation during perception could reliably predict which stimuli were being imagined or held in VWM, pointing towards some similarity in neural activity between these three processes. However, the generalisation was not perfect, potentially because internally generated images are more variable than perceptually derived images. These findings suggest that VI and VWM are highly similar but are not identical.

Pearson (2019) argued that there is substantial evidence for a relationship between working memory and visual imagery, one such line of evidence being that the tasks have similar capacity functions, that is, they appear similarly affected by increasing set-size. Indeed, if VMst and visual imagery are similar processes, then they should exhibit similar capacity limits. Many have suggested a capacity for VWM and VSTM of ~4 (+/-1) items (Cowan, 2001; Luck & Vogel, 1997), although this can be characterised as a resource distributed across targets rather than a fixed number of items (Bays & Husain, 2008) as has also been suggested for perceptual representations of attended objects (Howard & Holcombe, 2008). Relative to the VMst literature, there has been little work examining capacity limits in imagination. Recently Keogh and Pearson (2017) investigated capacity limitations in imagery by using an innovative binocular rivalry paradigm. Participants were presented with a number of placeholders and asked to imagine red-horizontal or green-vertical lines inside the holders. After which, participants were presented with a binocular rivalry display (e.g., the stimuli presented to the two eyes were different from one another, and this display produced binocular rivalry) at one of the previous placeholder locations. This was used to probe the prior image. Participants reported their overall perception by choosing: red-horizontal, green-vertical or mixed. If the choice made by the participant matched the imagined object then this was deemed as imagery priming perception. Priming strength from imagery decreased with increasing set-size and with increasing complexity, reflecting a limited capacity of imagination and reduction in precision of imagery as load increased, similar to findings in visual memory (Bays & Husain, 2008). Critically however, Keogh and Pearson's (2017) task did not probe what was actually represented, measuring only the impact imagery had on a subsequent task. This does not enable direct estimation of the capacity of visual imagery.

The current study presents a new paradigm that enables direct measurement of imagery and VWM from which capacity can be estimated and compared between tasks. Previous approaches to studying the similarities between imagery, perception and VWM have tended to present stimuli that have to be memorised (Johnson & Johnson, 2014; Lee et al., 2012) or manipulated (Albers et al., 2013). For example, Dijkstra et al. (2017) presented participants with two pictures, and then cued participants to imagine one of them. In this instance, the process corresponds strongly with visual memory because participants did not generate the original stimulus, instead they were previously presented with the stimulus. This means that what is being measured during imagery is influenced both by sensory and mnemonic processing. Crucially, the shared influence of low-level sensory stimulation from imagery and memory representations of specific images may have contaminated attempts to compare processing between perception, attention and imagery. The new paradigm presented here requires participants to generate an imagined block in visual imagery within a visible 6x6 grid. During image generation participants were presented with the grid and two arrow cues (one in the column, one in the row) and asked to imagine the black block at the intersection of the arrow cues as black instead of white. The to-be-imagined array is built up sequentially, with subsequent screens indicating to imagine another black block at a cued location, the number of screens determined by set-size (3-7). Once set-size is reached participants are then tested on the veracity of their imagination by being represented with a test array that is either the same or different to the to-be-imagined array. Importantly, the cues enable the online build-up of an imagined array and as such allows for a direct test of what is being imagined. This contrasts with the method used by Keogh and Pearson (2017), which assessed imagination priming on the subsequent binocular rivalry. Furthermore, the current study uses arrow cues to cue the to-be-imagined location instead of presenting placeholders at locations, the latter of which provides a substantial memory trace and thus could be argued to be measuring memory processes rather than imagery per se. Equally importantly, this method also allows assessment of VWM using an analogous task where the black blocks are visibly presented at locations within the grid. Both tasks therefore require participants to build up an image in the same way, however, in one task (imagination) the black blocks are imagined and in the other (VWM) they are seen. These two tasks will allow for one of the strongest tests of the relation between these two cognitive processes to date and provide capacity estimates for visual imagery and VWM.

The study aims to determine if capacity of VWM is the same or different to that of visual imagery. Given previous findings in imagery (Keogh & Pearson, 2017) and VWM (Cowan 2001) the expectation is that both imagery and VWM will be severely capacity limited. However, it is expected that capacity estimates will be higher in the VWM task than in the imagination task. This was expected given that imagery produces more variable activation patterns than are produced when visually perceiving an item (that is later processed in memory), and potentially engages different cognitive systems (Albers, et al., 2013; Pearson et al, 2015; Pearson, 2001; Logie, 1995, 2003, 2011). Furthermore, the increase in activation from top-down processes during imagery in comparison to viewed stimuli could be indicative of imagery requiring extra resources to enhance the visual representation (Dijkstra et al., 2017). It is also expected that performance (and capacity) on the two main tasks measuring imagery and VWM will positively correlate with one another given that behavioural and neuroimaging studies typically find positive relationships between imagery and VWM (Albers et al., 2013; Harrison & Tong, 2009; Kosslyn et al., 2001; Keogh & Pearson, 2014).

Finally, additional questionnaire measures such as the VVIQ (Marks, 1973), Revised Creativity Domain Questionnaire (CDQ-R; Kaufman et al., 2009), mathematical proficiency questions, and a series of strategy questions relating to the imagination task were developed. In addition, the forward Corsi block task was used as alternative measure of VWM capacity (Vandierendonck, Kemps, Fastame, & Szmalec, 2004). These additional measures were used to explore the association between individual differences, visual imagery and VWM within and across experiments.

5.2 Method

5.2.1 Participants

Twenty-eight participants (20 Female) took part in the experiment aged between 19 and 30 years (*M* = 24.1, *SD* = 3.3) and had normal or corrected to normal vision. Three participants did not complete all measures due to a computer malfunction. Each participant received a total of £10 for completing the 120-minute study and were recruited from a participant research panel. Data collection was approved by Nottingham Trent University's Business, Law and Social Sciences Research Ethics Committee.

5.2.2 Apparatus and materials

All experiments were run on a Lenovo ThinkCentre M79 10J7 using a 24" monitor (60-Hz refresh rate) with a 1360*768-pixel resolution. The imagination and visual working memory tasks were programmed using Psychopy 1.84.2 (Peirce, 2007). Colour is expressed between values of 1 and -1 as colour is expressed from deviations from a grey scale in Psychopy (Peirce, 2007). The Corsi task was run using Millisecond Inquisit Lab 5 software. A viewing distance was set at 57cm for each of the tasks. An online questionnaire was administered before the laboratory tasks using Qualtrics to measure imagery vividness, creativity and mathematical proficiency. An online questionnaire measuring strategies used during the imagination task was administered using Qualtrics after completion of the imagination laboratory-based task.

Vividness of Visual Imagery Questionnaire (VVIQ)

The VVIQ consists of 16 items which investigates the vividness of an individual's experience of visual imagery (Marks, 1973). It is a self-report inventory which consists of four subsections that each require participants to generate a mental image of specific scenes and situations (e.g., 'think of some relative or friend whom you frequently see - but who is not with you at present - and consider carefully the picture that comes before your mind's eye'). Subsequently, 4 items relating to each mental image are investigated (e.g., 'the exact contour of face, head, shoulders and body'). Each item is based on 5-point rating scale (1= 'Perfectly clear and as vivid as normal vision to me' to 5 = 'No image at all, you only "know" that you are thinking of the object'). The total score ranges from 16-80 for each participant with *low* scores indicating vivid imagery. The VVIQ has been widely reviewed and has been found to have very good internal consistency and reliability: Cronbach's α = .88-95 (Campos & Pérez-Fabello, 2009) with Mark's (1973) original study finding Cronbach's α = .89 and good construct and criterion validity. In the current study all items produce high internal reliability with Cronbach's α = .94.

Revised Creativity Domain Questionnaire (CDQ-R)

The CDQ-R investigates self-reported creativity (Kaufman et al., 2009). The inventory consists of 21 items and four factors: arts (e.g., painting), drama (e.g., acting), interaction (e.g., leadership) and maths/science (e.g., logic). Participants' were required to answer each item by making a judgment on their creative abilities in relation to other people who have a similar background to themselves. Each item requires a response on a scale of 1 'not at all creative' to 6 'extremely creative'. Item scores are totalled, and a score of between 21-126 can be obtained with high scores indicating creative abilities. In addition, factors are individually calculated. Arts contains three questions with a score of between 3-18 and all other factors contain six questions, each with a score of between 6-36. All factors produce high internal reliability with $\alpha = .82$ Cronbach coefficient across factors (Silvia et al., 2012). In the current study all factors produce high internal reliability with $\alpha > .87$ Cronbach's across factors.

Strategy questions (imagination).

A series of questions were developed to investigate the strategies used by participants for the imagination task. In total there were seven items. 6 items were rated on a 5-point Likert-style scale that ranges from 1 'fully disagree' to 5 'fully agree' and contained questions such as 'After the cues were presented, I used them as I was asked to'. There was no total score, each item represented a separate score. 1 item requires participants to 'describe the strategy used to complete the task?'.

Mathematical proficiency inventory

Questions were developed to investigate an individual's self-prescribed ability in understanding problems and concepts relating to mathematics. The inventory consists of 3 items ('my comprehension of mathematical concepts and operations is', 'my ability to solve mathematical problems is' and 'my capacity for logical thought is'). Each of the items are rated on a 5-point rating scale that ranges from 1 'very poor' to 5 'very good'. Item scores are totalled, and a score of between 3-15 can be obtained with higher scores indicating a self-perscribed mathematical disposition. All factors produce high internal reliability with Cronbach's $\alpha = .88$.

5.2.3 Design and procedure

Overview of procedure

A repeated measures design was used. Participants first completed the set of questionnaires followed by the 3 tasks (imagination, VWM and forward Corsi block). Tasks were counterbalanced using a Balanced Latin Square Design. After completion of the imagination task, participants were presented with the imagination strategy questions. The imagination and VWM tasks each consisted of 180 trials distributed equally across five set-sizes (3, 4, 5, 6, 7) with each task lasting approximately 50 minutes. The forward Corsi task included eight set-sizes (2-9) and consisted of 2 trials at each set-size, lasting approximately 5 minutes. The whole testing procedure lasted approximately 120 minutes.

VWM task

In the VWM task, participants had to remember a set of black blocks placed within a grid. The set of blocks were presented sequentially with each being added one by one until the full stimulus was visible. The number of blocks (set-size) was manipulated (3, 4, 5, 6 and 7). After a short delay, a test array was shown that either matched the sample array or differed by the placement of a single block. Participants made a 'same/different' response as to whether the test array was the same as or different from the stimulus in memory.

The onset of each trial began with text stating the word 'Ready' presented centrally for 500ms. A grid (6.72 cm x 6.72 cm) of 6 x 6 squares with light grey (0.5, 0.5, 0.5) lines on a white (1, 1, 1) background was then presented centrally for 1000ms. Each square of the grid was 1.12 cm by 1.12 cm with a 0.26cm light grey (0.5, 0.5, 0.5) line width and fill colour white (1, 1, 1). The grid remained on the screen and black blocks (-.2, -.2, -.2) sequentially populated random locations on the grid every 2000ms and remained on screen (Figure 5.1 bottom: VWM). Participants were asked to fixate the centre of the grid. This sequence was repeated for a length determined by the set-size on that trial (a set-size of 5 comprised a stimulus with 5 black blocks). The grid remained on the screen throughout this sequence. Immediately following the final presentation, a dynamic visual white noise mask (6.72 cm x 6.72 cm) was presented at the array location for 1000ms. The test array was then presented containing black blocks (-.2, -.2, -.2) either in in the previously cued locations (on same trials) or with one of these blocks moved by 2 squares either horizontally, vertically or diagonally (on different trials) with the constraint that no such moved block could be directly adjacent to any other black blocks (Figure 5.1: panel B). Participants responded either 'same', if that test array matched their memory by pressing the Z key or ‘different’, if the test array did not match their memory by pressing the M key. Participants were asked to respond as quickly and as accurately as possible. Following the response, participants were asked on a scale of 1 being least vivid to 4 being most vivid, ‘How vivid was your memory?’ Upon response corrective feedback was provided with “Correct” or “Incorrect” being presented centrally for 500ms.

At the beginning of the task was a 10-trial practice block. Participants then completed 180 trials across 3 equally balanced main blocks. Within each block, each set-size (3, 4, 5, 6, 7) was presented 12 times, there were 6 same trials and 6 different trials, all presented in a random order. Participants were able to take a short break after completing each block.

Imagination task

The imagination task was identical to the VWM task, except that no squares turned black. Instead, participants sequentially built up an image of a set of black blocks in their mind, with arrow cues presented at the top of a column and the left side of a row indicating that a block should be imagined at the intersection of that column and row (Figure 5.1: panel A). Arrows changed position every 2000ms with the sequence dependent on set-size. Immediately following the final presentation of arrow cues, cues disappeared. The test array was shown as per the VWM task, with vividness ratings also measured (with 10 practice trials and 180 trials structured in the same way).

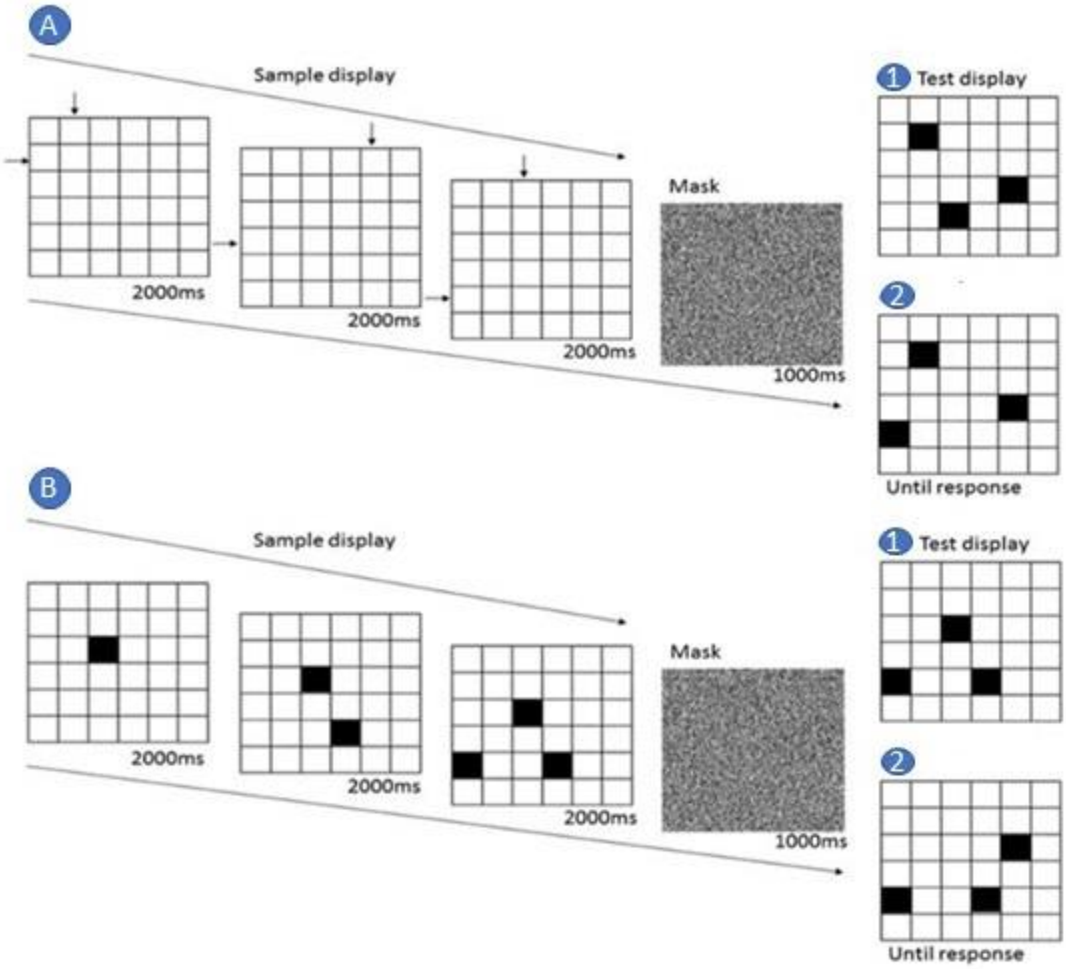

Figure 5.1. Trial sequence for a set-size 3 trial for the imagination (panel A) and VWM (panel B) tasks. In the imagination task - participants were asked to create black blocks in their minds eye at the intersections of the pairs of arrows whereas in the VWM task, blocks were visibly presented in the display. Example test displays in a 'same' trial (1) and 'different' trials (2) are shown.

<u>Forward Corsi block task</u>

This task was used as alternative measures of VWM capacity (Vandierendonck et al., 2004). Participants were required to reproduce a block sequence in the correct order that continually increased by one in length if the correct sequence was reproduced at least once out of two attempts. Participants began the task attempting to reproduce a 2-block sequence with 9 being the maximum block length tested. Each trial began with a display (3cm x 3cm) of 9 blue blocks for 1000ms. The first block of the sequence changed colour to yellow for 1000ms before returning to blue and the next block of the sequence being shown (Figure 5.2). After the full sequence on that trial was shown participants had to reproduce the sequence by clicking on the relevant squares with a mouse. If they made a mistake, they could press a reset button that allowed them to restart their response sequence. After each attempted sequence feedback was provided ("Correct" or "Incorrect" presented centrally).

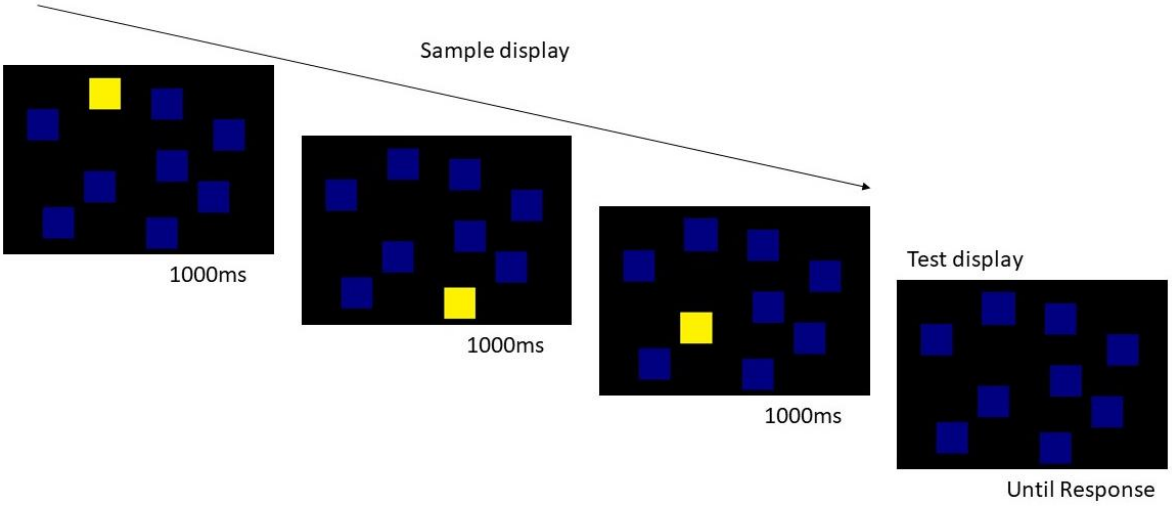

Figure 5.2. Example of a trial in the Corsi block task with a three-item sequence. Participants were asked to remember the sequence of yellow squares presented at test, they attempted to recall the sequence by selecting each relevant square on the test display in the correct order. In the Forwards version of the task, participants attempted to reproduce the sequence in the same order that was presented, whereas in the Backwards version the sequence had to be reproduced backwards (from last presented yellow square through to the first presented yellow square).

5.3 Results

5.3.1 Data preparation

Data were trimmed to exclude responses that were too fast (<300ms) or too slow (>6000ms). Data trimming limits were deemed acceptable to eliminate trials in which participants might not have been attending to the task sufficiently.

A programming error occurred during positioning of sample display stimuli; arrow cues and black blocks could not be assigned to the final column or bottom row of the grid. However, at test display, stimuli could be assigned to a position within the final column or bottom row. Thus, the error could affect how accurate participants were at responding to ‘different’ trials. This affected both imagination and memory data. 19.3% of imagination trials and 20% of memory trials were affected. In order to determine if display error affected participants’ accuracy a paired *t* test was completed on proportion correct data for display error and no error on each of the data. There was a significant effect for imagination data, response accuracy increased when the program created a display error, $t(27) = 3.70$, $p < .001$, $d = 1.42$. There was also a significant effect for memory data, response accuracy increased when the program created a display error $t(24) = 1.71$, $p = .05$, $d = .70$. The trials affected by display error were removed from analysis.

5.3.2 Statistical analysis

For the memory task, a repeated measures analysis of variance (ANOVA) was carried out on set-size (3, 4, 5, 6, 7) for accuracy (*d*’) and mean vividness ratings in two separate ANOVAs. The same ANOVAs were repeated for the imagination task. Post hoc analysis using Bonferroni corrections were used to investigate significant differences. Analysis focuses on *d’* for set-size accuracy as this is an unbiased measure of sensitivity as it takes account of hits and false alarms. Analysis on proportion correct is only presented if it yielded a different outcome to *d*’. Values of skew and kurtosis were deemed approximately normal if skew is between -2 to +2 and kurtosis -2 to +2 (George & Mallery, 2010). Normality of residuals was checked using the Shapiro-Wilk test (Ahad et al., 2011). If considerable violations of ANOVA assumptions were found, then non-parametric analysis were presented along with the ANOVA analysis. Greenhouse-Geisser correction was applied for non-sphericity. Effect sizes for ANOVAs are reported using generalised eta squared. Eta squared was chosen as the measure of effect as it is comparable across different research designs (Baguley, 2009).

5.3.3 Visual working memory results

The means and standard deviations for proportion correct for set-size on memory and imagination are shown in Table 5.1. Figure 5.3 (top) shows *d’*-prime for memory and imagination trials. A repeated-measures ANOVA conducted on memory *d*’ with set-size as a factor (3, 4, 5, 6, 7). There was no main effect of set-size, F(3.66, 87.75)= .509, p = .713, $\eta_g^2 =$ .02. As d' for the memory task violated tests of normality due to a celling effect, the Friedman non-parametric version of the ANOVA was used to examine if non-normality affected the ANOVA result. d' for the memory task for set-size (three, four, five, six, seven) showed no evidence of a difference in d' between these set-sizes, x_F^2 (4) = 4.2, p = .390. The ceiling effect was probably driven by the blocks in the memory task remaining onscreen until the mask was presented. This provided a lot of time to process these objects (e.g., 14 seconds for the first block in set-size 7) allowing for deep processing and potential transference into long term memory which therefore allowed participants to retain set-size with relative ease (Cowan, 1995).

Table 5.1. Mean and standard deviations (parenthesis) for proportion correct for task (imagination and VWM) across set-size (3, 4, 5, 6 and 7).

	Memory	Imagination
Set-size	Proportion correct	Proportion correct
3	.94 (.07)	.84 (.12)
4	.96 (.05)	.77 (.12)
5	.95 (.09)	.75 (.13)
6	.96 (.06)	.70 (.13)
7	.96 (.05)	.66 (.12)

Figure 5.3 (bottom) shows mean vividness scores as a function of set-size for memory and imagination. Vividness ratings tended to be high with a ceiling effect and little change over set-size. A repeated-measures ANOVA was conducted on mean vividness scores with set-size as a factor (3, 4, 5, 6, 7). There was no main effect of set-size, F(2.36, 56.71)= 1.01 p = .381, $\eta_g^2 =$ .04. As memory data on vividness violated tests of normality due to the ceiling effect, the data was analysed with the Friedman non-parametric version of the ANOVA as a check to determine if non-normality of the data affected the ANOVA result. Mean vividness scores in the memory task for set-size (3, 4, 5, 6, 7) showed no effect of set-size, x_F^2(4) = 1.93, p = .749.

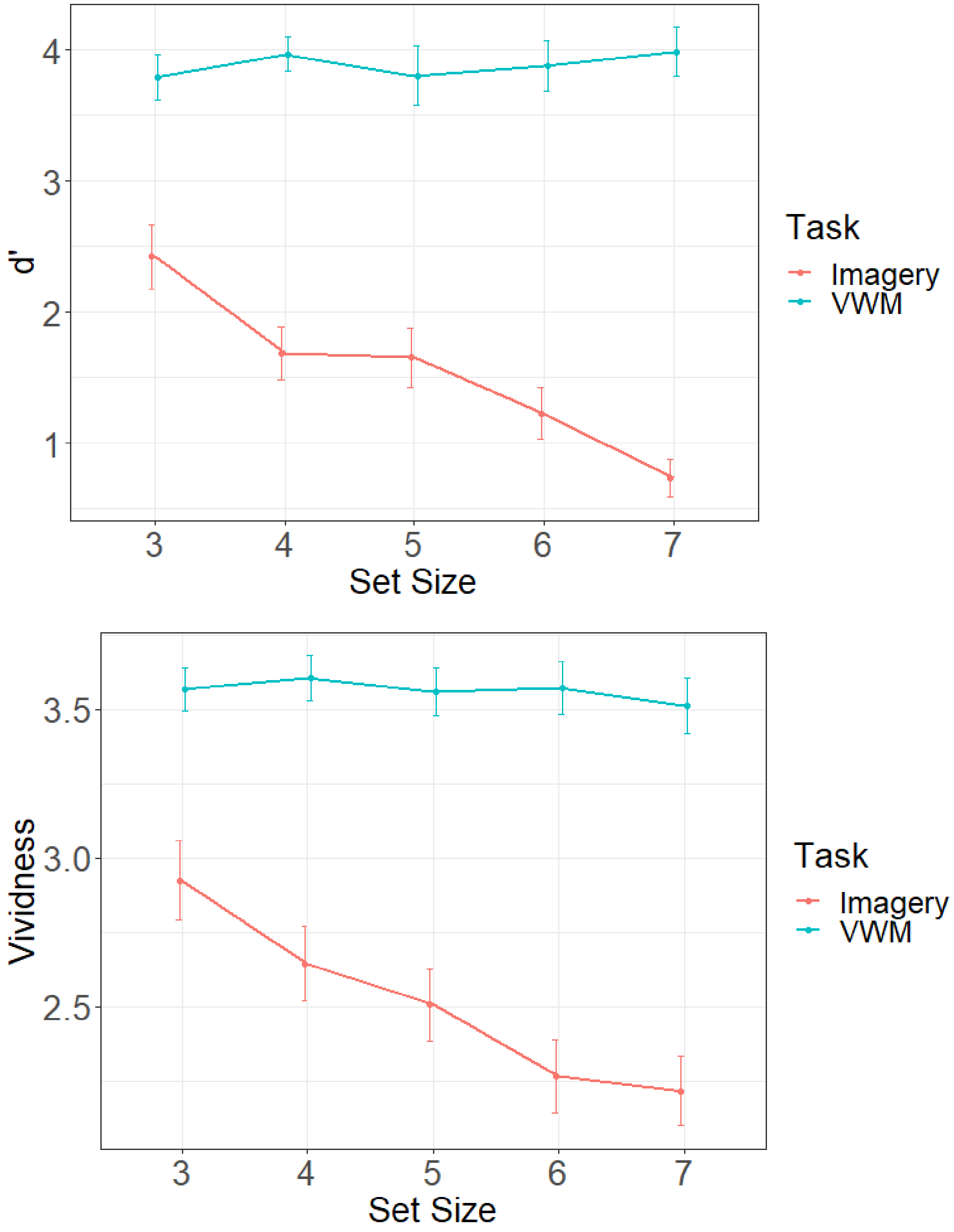

Figure 5.3. *d*’ (top) and (bottom) vividness as a function of set-size for the imagery and VWM (error bars indicate standard errors).

5.3.4 Imagination results

Figure 5.3 (top) shows a large reduction in *d'* as set-size increases. This contrasts with the memory results which appear to have been influenced by a celling effect. A repeated-measures ANOVA was conducted on *d*' with set-size as a factor (3, 4, 5, 6, 7) yielded an effect of set-size, *F*(4, 108)= 19.65, *p* < .001, $\eta_g^2 = .48$, with a significant linear trend, *F*(1, 27)= 53.57, *p* < .001, signifying that as set-size increased, performance decreased approximately linearly.

In Figure 5.3 (bottom), mean imagery vividness scores can be seen as a function of set-size. There is a large reduction in vividness as set-size increases. A repeated-measures ANOVA with set-size as a factor was performed on mean vividness scores. Mean imagery vividness decreased as a function of set-size, *F*(2.07, 55.76)= 36.57, *p* < .001, $\eta_g^2 = .57$, with a significant linear trend, *F*(1, 27)= 55.05, *p* < .001 and a significant quadratic trend, *F*(1,27)= 6.09, *p* = .020, signifying that as set-size increased, vividness scores decreased substantially at first but then by diminishing amounts. In comparison, memory was influenced by a celling effect with memory vividness scores remaining consistent with increasing set-size.

5.3.5 Modelling procedure and Capacity Estimates

The WoMMBAT (Working Memory Modelling using Bayesian Analysis Techniques; Morey & Morey, 2011) was used to model capacity of imagination. VWM data could not be modelled due to the ceiling effect. Morey's WoMMBAT model forms a hierarchical Bayesian extension from the non-hierarchical model developed by Rouder et al. (2008) and the formula established by Pashler (1988) for whole display change detection. The model is well suited to the aims of the current study because it produces an overall capacity estimate (*k*) and also capacity estimates for each individual (for a comprehensive review about the WoMMBAT model see section 4.1.3).

Modelling was completed by fitting the WoMMBAT model to data in R (Morey & Morey, 2011). Data entered were trial level data on the imagery task, indicating the participant, set-size, whether the trial was a change trial and whether the response was correct response (whether the participant responded “change”).

The WoMMBAT model provides three parameter estimates: *k*, the number of items maintained in imagination, *z*, an attentional lapse rate, and *g* guessing bias (Morey, 2011). Parameters *k*, *z* and *g* were included in all models with parameters *k* and *g* allowed to vary between participants.

Parameter z was fixed for all participants (Morey, 2011). The parameters k and g varied between participants. The prior parameter settings were set at; U^Kmean: 3 , U^z mean: 0 , U^g mean: 0, each with a standard deviation of 10 Inverse gamma a_0 and b_0 were set at 2 and 1, respectfully. The inverse Wishart prior was set at 2. All the prior parameters are reasonable defaults according to Morey and Morey (2011).

To obtain parameter estimates the WoMMBAT model uses Markov chain Monte Carlo (MCMC) estimation. The length of the chain is controlled by a number of factors including the number of iterations (set to 300,000) and the number of burn-in iterations where a number of iterations at the beginning of the chain are discarded to minimise the influence that the first iterations can have on the chain (set to 5,000). The reason for this long chain was to mitigate the potential effect of high autocorrelation within the MCMC chain which is associated with the whole display design (Morey, 2011). Finally, the MCMC method is the *hybrid Monte Carlo* (Liu, 2001) method which has two parameters: $\epsilon \; and \; N_{if}.$ ε refers to how finely time is approximated and N_{if} represents the number of time simulation steps performed. The WoMMBAT model has two parameters for ε, a lower and an upper value, and in each sample the ε value is sampled uniformly. Adjusting these parameters influences the time taken to run a simulation, with a trade-off in terms of the time taken and the quality of the simulation. The overall goal of the WoMMBAT model is to create good quality MCMC chains in the least amount of time by using the smallest possible values on $\epsilon \; and \; N_{if}$ (Morey, & Morey 2011). The *hybrid Monte Carlo* parameters were set at; ε = 4, lower N_{if} = 0.001, upper N_{if} = 0.010 and are in accordance with the recommended guidance set out by Morey and Morey (2011).

MCMC chain sample acceptance rates were in the range deemed to be good (between .60 and .90; Table 5.2). In addition, WoMMBAT provides a graphical method for checking the quality of the MCMC chains and thus whether they will produce good parameter estimates. For each parameter three plots are produced to assess whether the chains converge. The first is the MCMC chain plotted as a function of MCMC iteration, which should appear as random noise. The second is the kernel density estimate which shows the marginal posterior distribution of the parameter. The third is the autocorrelation function of the MCMC chain, which for an ideal chain is 0 (for full details see Morey, 2011).

Table 5.2. Hierarchical Bayesian model fit statistics for whole display change detection data for the imagination task.

Model	Number of parameters on *k*	DIC	pD	Acceptance rate
Participant variance: imagination	28	4245.7	33.1	.76

Note. *N* = 28.

The analysis produced good acceptance rates and no specific trend could be clearly identified in the MCMC chain (Figure 5.4). However, there was an issue with the autocorrelation function (Figure 5.4). Ideally each iteration produced by the MCMC chain should be almost independent from the previous iteration. The current model showed dependency between iterations which can reduce the reliability of the MCMC analysis. However, it is important to note that the model provided acceptable accuracy rates, MCMC iteration plots and posterior density plots (Figure 5.4) and issues with autocorrelation were predicted due to the difficulties associated with whole display designs (Morey, 2011).

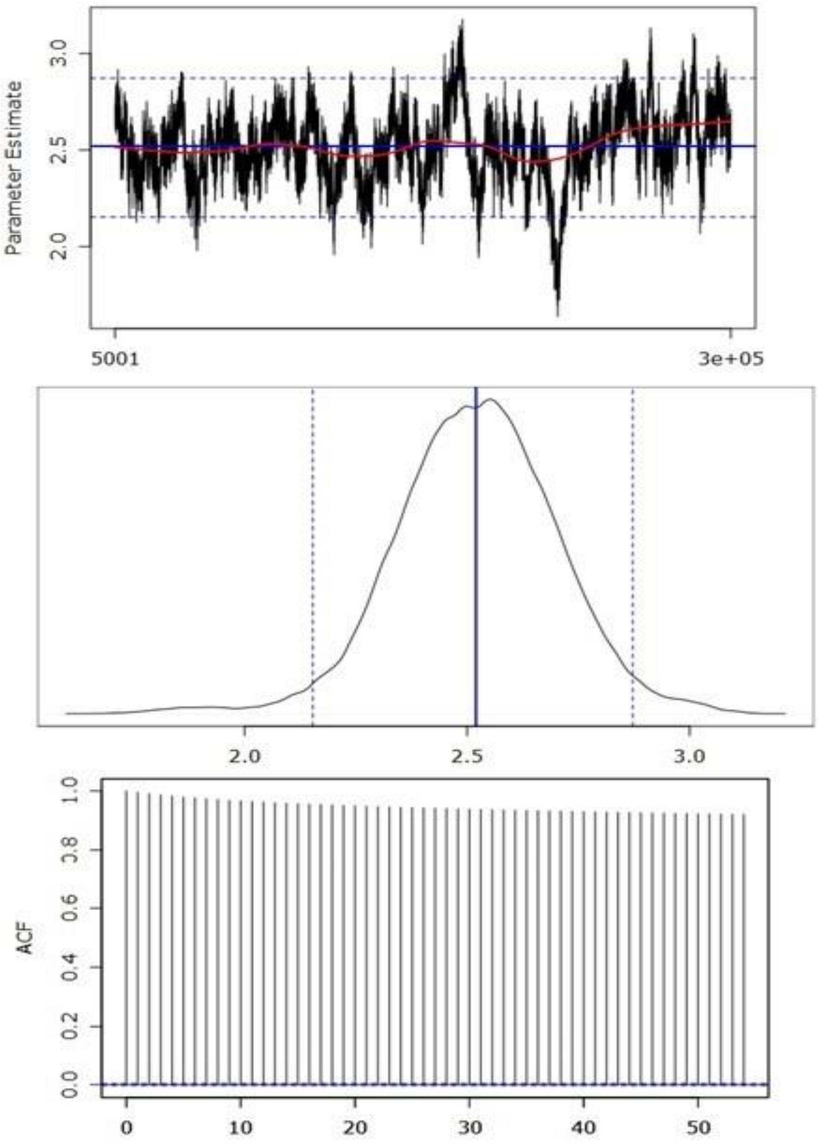

Figure 5.4. MCMC chains: iterations plots (top), Kernel density plots (centre) and autocorrelations plots (bottom).

In total, 28 parameters were estimated for each of *k* and *g*. Model fit statistics can be found in Table 5.2. The model estimated that 2.54 items can be maintained in imagination. Individual capacity estimates are provided in Figure 5.5. In order to investigate the reliability of the results, further analysis was conducted using Rouder et al's. (2008) extension of Pashler's (1988) whole display change detection capacity model.

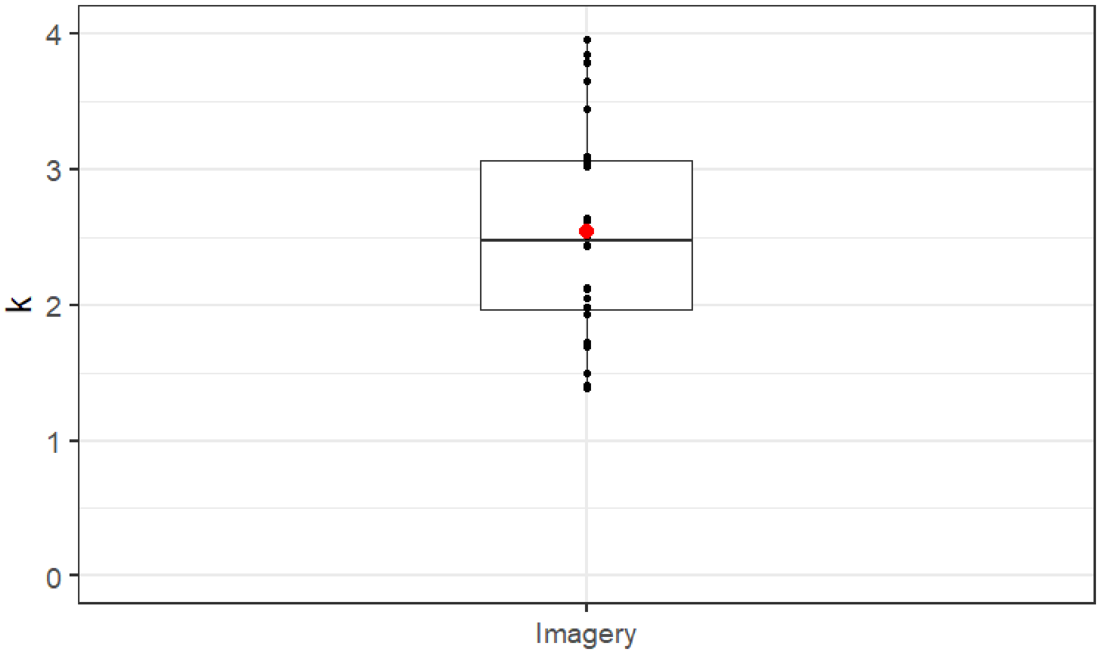

Figure 5.5. Capacity estimate (*k*) for each participant in the imagery task.

Predicted values of *d*' were generated using Rouder et al's. (2008) whole display model. The model was fit to data from all individuals simultaneously (140 data points, 5 data points per participant) to derive a single prediction for capacity (*k*). The model was fit by minimising R^2 (Guest et al., 2015). Individual capacity estimates could not be modelled due to non-linearity in the mean performance at each set-size. Figure 5.6 shows the observed and predicted *d*' data from the Rouder et al. (2008) model as a function of set-size. The model yielded a *k* of 2.48 and a *u* (uninformed guessing) of .18, with an R^2 value of .26. This model predictions fit the data relatively well and the estimate of a capacity of 2.48 items is comparable to the 2.54 estimate from the WoMMBAT model. Crucially, both estimates indicate that imagination has reduced capacity compared to that typically estimated for VWM (~4 items).

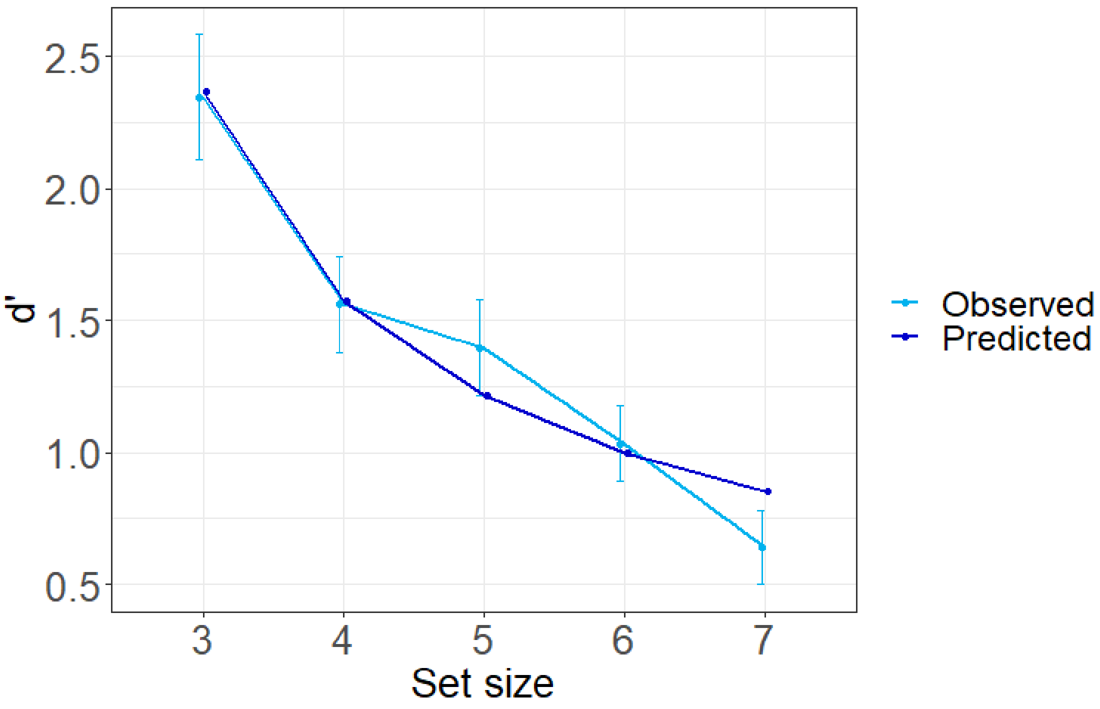

Figure 5.6. Averaged individual observed *d*' and predicted *d*' as a function of set-size for imagination.

5.3.6 Correlations

The means and standard deviations of questionnaire measures and the Corsi block task are reported in Table 5.3. Correlations were not computed on the memory data due to the ceiling effect. Therefore, all measures below are only compared to the imagination data. Correlations were computed on the data of 28 participants. Table 4 presents correlations between *d*', Corsi block task scores and questionnaire measures. Table 5 presents correlations between *d*' and imagination strategy questions.

There were several findings of note. First, there was no relation between Forward Corsi Span and imagination (see Table 5.4). This suggests that there is not a relationship between the VWM measure of Corsi span and visual imagery. However, within the working memory model it has been argued that the forward Corsi Span task engages slave systems of working memory (visual-spatial sketchpad). It might be that memory and imagination potentially engage separate short-term maintenance systems; however, this cannot be concluded simply on the basis of relationships with Corsi span. Secondly, no relation was found between the VVIQ (Marks, 1967) and performance on the imagination task (see Table 5.4). This might be because

VVIQ does not assess object and spatial imagery, instead the VVIQ primarily assess object imagery (Kozhevnikov et al., 2005; Blazhenkova, 2016). However, previous research using a binocular rivalry task also found no correlation between the strength of a visual image and the VVIQ (Dijkstra, Hinne et al., 2019). This may indicate that the VVIQ might be an incomplete measure of vividness. Thirdly, an association was found between mathematical proficiency and imagination *d'* (see Table 5.4). Previous research has associated working memory performance and skill in arithmetic problem solving with faster processing (Geary & Widaman, 1992). However, to date, limited research has investigated the link between imagination and mathematical proficiency, with Abrahamson (2006) calling for research into the mechanisms and agency of imagination in mathematical reasoning. Finally, there was no relationship between performance and use of strategy, suggesting that individual cognitive preferences (e.g., using phonological encoding) were not driving performance differences within the task (see Table 5.5).

Table 5.3. Descriptive results of imagination strategy questions (1-6), Corsi block task, VVIQ, CDQ-R and subscales and mathematical proficiency.

	N	*M*	*SD*
After the cues were presented, I used them as I was asked to	28	4.14	0.76
I often *did not* imagine the objects	28	2.32	0.82
When tested I remembered the cues instead of thinking about the imagined objects	28	2.82	0.98
I used words and/or sentences to help myself remember	28	2.18	1.36
I used numbers to help myself remember	28	2.61	1.62
After the cues I vividly imagined the object, as if I could see it in front of me	28	3.46	1.00
Corsi span	25	6.08	1.26
Corsi total score	25	56.88	22.81
VVIQ	25	38.88	10.31
CDQ-R total score	25	68.24	14.90
CDQ-R Drama	25	17.92	5.52
CDQ-R maths and science	25	17.64	6.18
CDQR arts	25	10.64	2.90
CDQ-R interaction	25	22.04	4.84
Mathematical proficiency	25	11.60	2.71

Table 5.4. Correlations among capacity (*k*), *d*’, VVIQ, CDQ-R and subscales and mathematical proficiency.

		1	2	3	4	5	6	7	8	9	10	11
1	Imagination *k*	-										
2	Imagination *d*'	**.90****	-									
3	Corsi span	.16	.31	-								
4	Corsi total score	.12	.28	**.99****	-							
5	VVIQ	-.15	-.11	.03	.06	-						
6	CDQ-R total score	-.09	.07	-.17	-.17	-.15	-					
7	CDQ-R Drama	-.24	-.13	-.22	-.18	-.19	**.73****	-				
8	CDQ-R maths and science	-.01	.11	-.16	-.16	-.19	**.90****	**.53****	-			
9	CDQR arts	.08	.24	.01	-.01	-.08	**.63****	.30	**.51****	-		
10	CDQ-R interaction	-.05	.06	-.08	-.11	.05	**.73****	.25	**.57****	.36	-	
11	Mathematical proficiency	.28	**.44***	.15	.12	-.26	**.54****	.23	**.46***	.36	**.58****	-

Note. *N* = 25, two-tailed test; **p* < .05, ** *p* < .01.

Table 5.5. Correlations among capacity (*k*), *d*' and strategy questions.

		1	2	3	4	5	6	7	8
1	Imagination *k*	-							
2	Imagination *d*'	**.92****	-						
3	After the cues were presented, I used them as I was asked to	-.12	-.15	-					
4	I often did not imagine the objects	-.24	-.26	-.32	-				
5	When tested I remembered the cues instead of thinking about the imagined objects	-.23	-.23	**-.46***	**.44***	-			
6	I used words and/or sentences to help myself remember	-.31	-.31	-.28	**.45***	.25	-		
7	I used numbers to help myself remember	-.11	-.15	-.35	.30	.33	**.52****	-	
8	After the cues I vividly imagined the object, as if I could see it in front of me	.14	-.04	**.40***	-.10	-.29	-.23	.00	-

Note. *N* = 28, two-tailed test; * *p* < .05, ** *p* <.01.

5.4 Discussion

The study was designed to determine if capacity of visual imagery is the same or different to that of VWM. Prior research suggests that imagery and VWM are related (Harrison & Tong, 2009; Keogh & Pearson, 2011, 2014; Kosslyn & Thompson, 2003) and show some similarity in neural activation patterns in the visual system (Albers et al., 2013; Johnson & Johnson, 2014; Lee et al., 2012). Previous approaches to studying the similarities between imagery, perception and VWM have tended to present stimuli that have to be memorised (Johnson & Johnson, 2014; Lee et al., 2012; Dijkstra et al., 2017) or manipulated (Albers et al., 2013). In these instances what is being measured during imagery is influenced both by sensory and mnemonic processing. Crucially, the shared influence of low-level sensory stimulation from imagery and memory representations of specific images may have contaminated attempts to compare processing between imagery and VWM. Whilst it is known that imagery is capacity limited

(Keogh & Pearson, 2017), the capacity of imagery in terms of the number of imagined objects has never previously been measured.

Based on previous literature it was expected that imagery and VWM would be severely capacity limited with imagination capacity being lower than that of VWM. It was also expected that the two tasks would positively correlate with one another.

The present study demonstrated that imagery performance (*d*') and vividness were reduced with increase in set-size. A ceiling effect was found in the VWM task. VWM capacity could not be modelled due to the ceiling effect, nor could a relationship be established between VWM and imagery. Capacity estimates showed that imagination is severely capacity limited compared to typical estimates of VWM capacity (~4 items; Cowan, 2001, 2005; Luck & Vogel, 1997; Zhang & Luck, 2008). However, it is difficult to interpret the capacity limit for imagination because the ceiling effect for the VWM task prevented capacity being estimated for VWM, and this is the most useful comparison as the tasks were designed with a similar methodology. As such, interpretation of the capacity in imagination is left to the general discussion at the end of this chapter. It is probable that the VWM ceiling effect was due to the gradual build-up of the memory display with each block remaining on screen once it had appeared. This may have allowed much deeper processing than in typical memory displays (e.g., transfer into long term memory) (Cowan, 1995).

5.5 Experiment 2

5.5.1 Introduction

Experiment 2 was designed to rectify the issues arising in Experiment 1. In Experiment 2, the VWM task was modified such that each block was presented for 2000ms before disappearing, instead of remaining on screen for the duration of the presentation of the sample array. This was intended to reduce potential long-term memory processing of stimuli (Cowan, 1995) which could have caused the ceiling effect in Experiment 1. In addition, a visual short-term memory (VSTM) task in which items were presented simultaneously was used to investigate its relationship to imagery and VWM. VSTM has been described as a short duration, high-capacity system and it has been suggested that it differs from other forms of short-term visual memory such as iconic memory and VWM (Sligte et al., 2008). The key difference between VSTM and VWM is that VWM tasks require active processing and maintenance of the stimuli to be remembered and thus may draw on a number of systems such as those hypothesised in working memory models (Baddeley, 2007; Cowan; 2017; Logie, 1995, 2011; for review of distinction between VSTM and VWM see Aben et al., 2012). Although change detection tasks like the current VSTM task have also been referred to as measuring VWM, the distinction between VSTM and VWM is made here on the basis of whether items in memory required manipulation (VWM) or not (VSTM) and not whether VWM and VSTM are theoretically distinct.

Experiment 2 involved a single queried block using a single post-cue at test. Although the same number of black blocks were presented in the test array as were presented in the sample array (as per Experiment 1), the response pertained only to one of these blocks which was highlighted within the test array. The participant had to decide if the highlighted block in the test array had previously occupied that same location or not in the sample array. The reason to employ a single post-cue was twofold: 1) to rectify issues associated with modelling whole display data (e.g., difficulties with autocorrelation functions, for discussion see Morey, 2011) 2) to reduce decisional processes to one item at test whilst maintaining imagery/memory load consistent with Experiment 1. At larger set-sizes, more decisions are required regarding the comparison between sample and test arrays which likely increases uncertainty (Beck & van Lamsweerde, 2011; Hollingworth, 2003; Luck et al., 1996). Therefore, whole display paradigms at larger set-sizes may be measuring decisional processes rather than capacity limitations per se.

Finally, the positioning of the grid was altered between presentations of the sample array and test array for each of the three tasks: If a sample array was presented to the left of the display, then the test array would be presented to the right of the display and vice versa. By presenting the test array adjacent to the sample display, this removed any interference from successive stimulus presentations at the same location. This allowed participants to keep their memory or imagination active whilst comparing this to the test array. It is well established that object representations can substitute and interfere with other object representations when presented in spatial and temporal proximity (Guest et al., 2011, 2012). Change detection paradigms typically use the same parts of space when presenting the sample arrays and test arrays. This could mask or disrupt visual images and so the methodology of Experiment 2 tried to ensure this would not be the case (Baddeley & Andrade, 2000; McConnell & Quinn, 2004; Quinn & McConnell, 2006).

Similar to the hypothesis for Experiment 1, it was predicted that visual imagery would be more capacity limited in comparison to visual memory in the short-term. It was expected that capacity estimates will be higher in the VSTM task and VWM task than in the imagination task, with capacity estimates being higher in the VSTM than the VWM. This was expected given that imagery produces a weaker visual representation than when visually perceiving an item (that is later processed in memory), potentially engages different cognitive systems (Cowan; 2017; Logie, 1995, 2011; Pearson, 2001; Pearson et al, 2015), and potentially requires extra resources to enhance the visual representation in comparison to viewed stimuli (Dijkstra et al., 2017). In addition, VWM is partly differentiated from VSTM due to the former having an active processing mechanism rather than just a maintenance component. This active process is more cognitively demanding than simply maintaining items in memory and thus disruption is likely caused by the higher cognitive demand placed upon the VWM system (Cowan; 2017; D'Esposito et al., 1999). Furthermore, given the wealth of behavioural and neuroimaging studies finding positive relationships between imagery and VM (Albers et al., 2013; Harrison & Tong, 2009; Keogh & Pearson, 201; Kosslyn et al., 2001), it was expected that the three tasks measuring imagery, VWM and VSTM will positively correlate with each other. It was expected that performance in the imagery task will more strongly correlate with performance in the VWM task compared to performance on the VSTM task due to the active processing of the information in the imagery and VWM tasks compared to the VSTM. It was also expected that performance in the VSTM task will more strongly correlate with performance in the VWM than the imagery task due to VSTM and VWM being similar in that VWM includes short-term memory as a part of its system (Cowan, 2008).

Finally, additional questionnaire measures such as the Vividness of Object and Spatial Imagery (VOSI; Blazhenkova, 2016) and a strategy question was developed that investigated an individual's strategy during the working memory task. In addition, the backwards Corsi block task was used as an alternative measure of VWM capacity. These additional measures were used to explore the association between individual differences, visual imagery and VWM within and across experiments.

5.5.2 Method

5.5.2.1 Participants

A convenience sample of forty-two participants (29 Female), aged between 19 and 34 years (*M* = 20.7, *SD* = 3.84) and with normal or corrected to normal vision took part. This was chosen as a generous sample in comparison with those of previous similar behavioural studies investigating visual imagery and VWM (*N* < 36; e.g., Keogh & Pearson, 2011, 2014, 2017). Each participant received a total of £15 for completing the 180-minute study. All data collection was approved by Nottingham Trent University's Business, Law and Social Sciences Research Ethics Committee.

5.5.2.2 Apparatus and materials

All tasks and questionnaires were repeated from Experiment 1 with the following exceptions: The VSTM task was programmed using Psychopy 1.84.2 (Peirce, 2007). The backwards Corsi block task was administered as well as the Forward task using Millisecond Inquisit Lab 5 software. An online questionnaire was administered by Qualtrics to measure VOSI and VWM self-report strategy. In addition, an extra question was added to the imagination strategy inventory asking. All details are explained below.

Vividness of Object and Spatial Imagery (VOSI)

Vividness of object and spatial imagery was assessed using a 28-item scale (Blazhenkova, 2016). This measure was introduced as it measures both object and spatial imagery. The self-report inventory comprises two factors that assess object and spatial imagery. Each factor is assigned 14 items. Object imagery probes an individual's ability to create colourful, vivid and specified objects (e.g., 'Appearance of a candle fire'), whereas spatial imagery items investigate spatial relations and transformation of imagery (e.g., 'motion of the planets on a model of the solar system'). Each item is based on 5-point rating scale (1= 'No image at all, you only "know" that you are thinking of the object' to 5 = ''Perfectly clear and vivid as normal vision'). Total scores range from 14-70 for each factor with high scores indicating vivid object imagery or vivid spatial imagery. A grand total for 28-items range from 28-140 with high scores indicating vivid object and spatial imagery. Each factor has been found to have convergent and discriminative validity and good internal reliability: object imagery Cronbach's α = .88 and spatial imagery Cronbach's α = .89 (Blazhenkova, 2016). From the current study, all factors produce high internal reliability with object imagery Cronbach's α = .90 and spatial imagery Cronbach's α = .86.

Strategy question (VWM)

The strategy question investigates the individual's strategy during the working memory task. The single question requires participants to 'describe the strategy used to complete the task'.

Strategy questions (imagination).

The strategy inventory was the same as experiment 1 with the exception that an extra item was added which asked, 'Did the arrows make it possible for you to know which cell you were to imagine the object in?' It was rated on a 5-point Likert-style scale that ranged from 1 'fully disagree' to 5 'fully agree'.

VVIQ

This is the same inventory that was administered in experiment 1. In the current study all factors produce high internal reliability with $\alpha = .86$ Cronbach's.

CDQ-R

This is the same inventory that was administered in experiment 1. In the current study all factors produce high internal reliability with $\alpha > .81$ Cronbach's across factors.

Mathematical proficiency inventory

This is the same inventory that was administered in experiment 1. In the current study all factors produce high internal reliability with $\alpha = .89$ Cronbach's.

5.5.2.3 Design and procedure

Overview of procedure

Participants first completed the set of questionnaires (VOSI, VVIQ, CDQ-R and mathematical proficiency) which were administered online. Upon completion, the imagination, VWM, VSTM, forward and backward Corsi block tasks were completed, the order counterbalanced across participants using a Balanced Latin Square Design, A repeated measures design was used. Once the imagination or working memory task was complete; questions were administered for each of these tasks regarding task strategies used. In total it took approximately 180 minutes to complete the study.

VWM task

The design and procedure were the same as Experiment 1 with the following exceptions. Each trial began with a light grey (0.5, 0.5, 0.5) fixation dot, presented on the left [position = X,Y (-337.5, 0)] or right [position = X,Y (337.5, 0)] of the display for 500ms, replaced at the same location by a light grey (0.5, 0.5, 0.5) 6x6 grid presented for 1000ms. Subsequently, the test array was presented on the opposite side of the display and comprised the grid containing black blocks in the previously cued locations ('same' trials) or with one of these blocks moved by 2 squares either horizontally, vertically or diagonally ('different' trials) with the constraint that no such moved block could be directly adjacent to any other black blocks The single post-cue was selected from any one of the presented black blocks on ‘same’ trials. On ‘different’ trials, the single post-cue was always the one that differed in location from its location in the sample array (Figure 5.7: panel B). The post-cue was presented with a highlighted white (1, 1, 1) outline colour, line width of .08 cm and fill colour black (-.2, -.2, -.2). Each of the other black squares of the grid were 1.12 cm by 1.12 cm with a 0.26 cm light grey (0.5, 0.5, 0.5) line width and fill colour black (-0.2, -0.2, -0.2).

Imagination task

The imagination task was identical to the VWM task, except that no squares turned black. Instead, participants sequentially built up an image of a set of black blocks in their mind, with arrow cues presented at the top of a column and the left side of a row indicating that a block should be imagined at the intersection of that column and row (Figure 5.7: panel A). Arrows changed position every 2000ms with the sequence dependent on set-size. Immediately following the final presentation of arrow cues, cues disappeared and a blank grid was presented for 1000ms. The test array was shown as per the visual working memory task, with vividness ratings also given (with 10 practice trials and 180 trials structured in the same way).

VSTM task

The VSTM task was identical to the VWM task except that the black blocks were presented simultaneously for 100ms followed by the mask (Figure 5.7: panel C). The test display and questions were identical. Set-size differed to the other tasks as piloting indicated the task was easier and so a greater range was used (3, 5, 7, 9). As such there were 144 trials across 3 blocks, with each block presenting each set-size 12 times (six same and six different trials) in a random order. Participants were able to take a short break after each block.

Forward Corsi block task

This is the same task that was administered in experiment 1.

Backwards Corsi block task

This is the same task as the forward Corsi block task with the exception that participants were asked to recall the exact sequence *backwards* (from last yellow square through to the first yellow square) by selecting each relevant square on the test display.

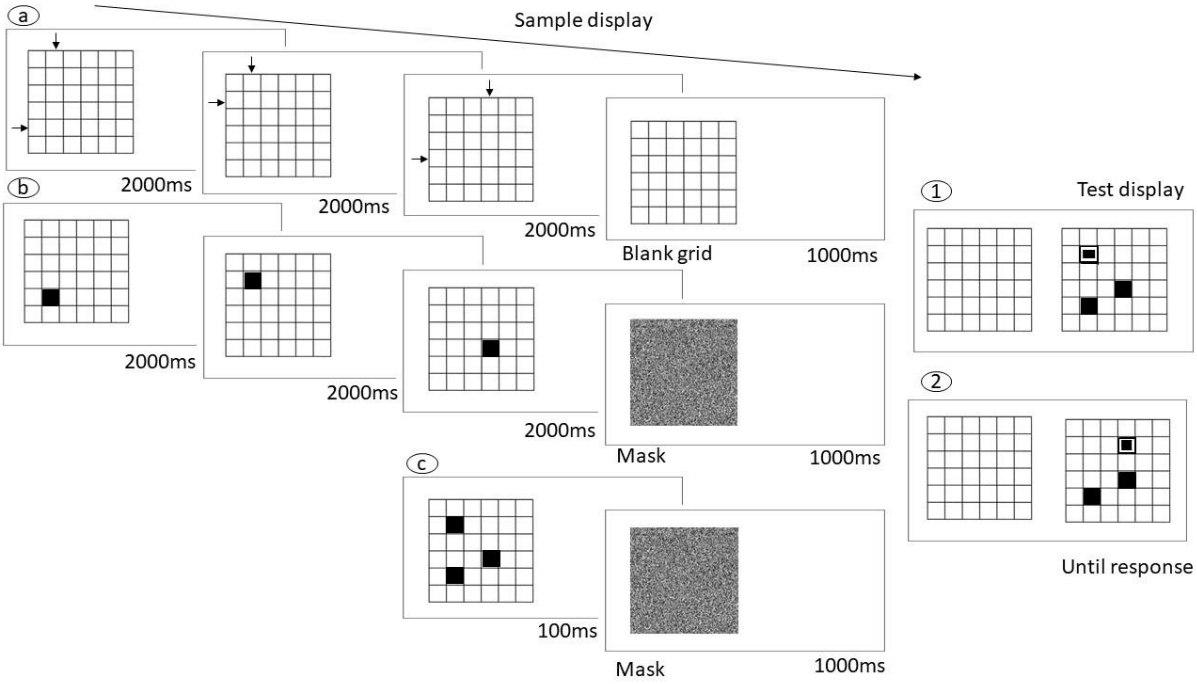

Figure 5.7. Stimuli and sequence of events in visual tasks with set-size 3 items. (a): Imagination task - participants were asked to create a black block in their minds eye at the intersection between the two arrow cues. (b): VWM task - black blocks were presented in a sequential manner. (c): VSTM task - all black blocks were presented simultaneously. (1) same trial (2) change trial.

5.5.3 Results

5.5.3.1 Data preparation

The data preparation was the same as Experiment 1. The main analysis included all participant data. Nine participants reported using alternative cognitive strategies (e.g., ‘I gave each black block a specific number to encode its location’). Statistical analysis was re-conducted with these participants removed. Since no evidence of a differences was found, only the main analysis is reported.

5.5.3.2 Statistical analysis

The statistical analysis was the same as Experiment 1 with the following exceptions. For the VWM and imagination tasks, a 2 (task: VWM, imagination) x 5 (set-size: 3, 4, 5, 6, 7) repeated measures analysis of variance (ANOVA) was carried out on performance (*d*') and vividness ratings in two separate ANOVAs. For VWM, imagination and VSTM tasks, a 3 (task: VWM, imagination, VSTM) x 3 (set-size: 3, 5, 7) repeated measures ANOVA was carried out on accuracy (*d*') and vividness ratings in 2 separate ANOVAs. In addition, a one-way ANOVA (set-size: 3, 5, 7, 9) was carried out on accuracy (*d*') and vividness ratings in two separate ANOVAs for VSTM.

5.5.3.3 Imagination and VWM results

The means and standard deviations for proportion correct for set-size on imagination, VWM and VSTM are shown in Table 5.6. Figure 5.8 shows *d'* (a) and vividness (b) for all tasks as a function of set-size. Performance in all tasks appeared to decrease at a similar rate as set-size was increased. Imagination *d*' and vividness is lower than that of VWM and VSTM, and VWM being lower than that of VSTM at each set-size. A 2 (task: VWM, imagination) x 5 (set-size: 3, 4, 5, 6, 7) repeated-measures ANOVA on *d*' yielded an effect of task, $F(1, 41)= 57.68$, $p < .001$, $\eta_g^2 = .26$, with VWM performance better than imagination performance. There was an effect of set-size, $F(4, 164)= 57.24$, $p < .001$, $\eta_g^2 = .37$, with a significant linear trend, $F(1, 27)= 53.57$, $p < .001$, and a significant cubic trend, $F(1, 27)= 53.57$, $p < .001$, signifying that as set-size increased, performance decreased approximately proportionally, however performance levels off between set-sizes but continued to decrease overall. No interaction effect was found, $F(4, 164)= .86$, $p = .487$, $\eta_g^2 < .01$.

A 2 (task: VWM, imagination) x 5 (set-size: 3, 4, 5, 6, 7) repeated-measures ANOVA on vividness yielded an effect of task, $F(1, 41)= 49.18$, $p < .001$, $\eta_g^2 = .39$, with VWM vividness being better than imagination. An effect of set-size, $F(1.75, 71.88)= 106.84$, $p < .001$, $\eta_g^2 = .44$, with a significant linear trend, $F(1, 41)= 53.57$, $p < .001$, and a significant quadratic trend, $F(1, 41)= 53.57$, $p < .001$, signifying that as set-size increases, vividness scores decreased linearly at first, and then at a diminishing rate as set-size increased. There was an interaction effect between task and set-size, $F(2.42, 99.02)= 3.07$, $p = .018$, $h_g^2 = .01$. Post hoc analysis found that VWM vividness decreased between set-size three and four ($p = .001$, $d = .70$), four and five ($p < .001$, $d = 1.14$), five and six ($p < .001$, $d = .82$) and no effect between six and seven ($p = .052$, $d = .46$). Imagination vividness decreased between set-size three and four ($p < .001$, $d = 1.26$), four and five ($p < .001$, $d = .83$), six and seven ($p < .001$, $d = .79$) and no effect between five and six ($p = .181$, $d = .38$).

Table 5.6. Mean and standard deviations (parenthesis) for proportion correct for set-size (3, 4, 5, 6 and 7) on imagery, VWM and set-size (3, 5, 7 and 9) for VSTM.

	Proportion correct		
Set-size	Imagery	VWM	VSTM
3	.80 (.12)	.87 (.12)	.91 (.07)
4	.73 (.14)	.83 (.12)	-
5	.68 (.13)	.80 (.12)	.82 (.10)
6	.68 (.11)	.76 (.13)	-
7	.60 (.11)	.71 (.11)	.75 (.11)
9	-	-	.67 (.10)

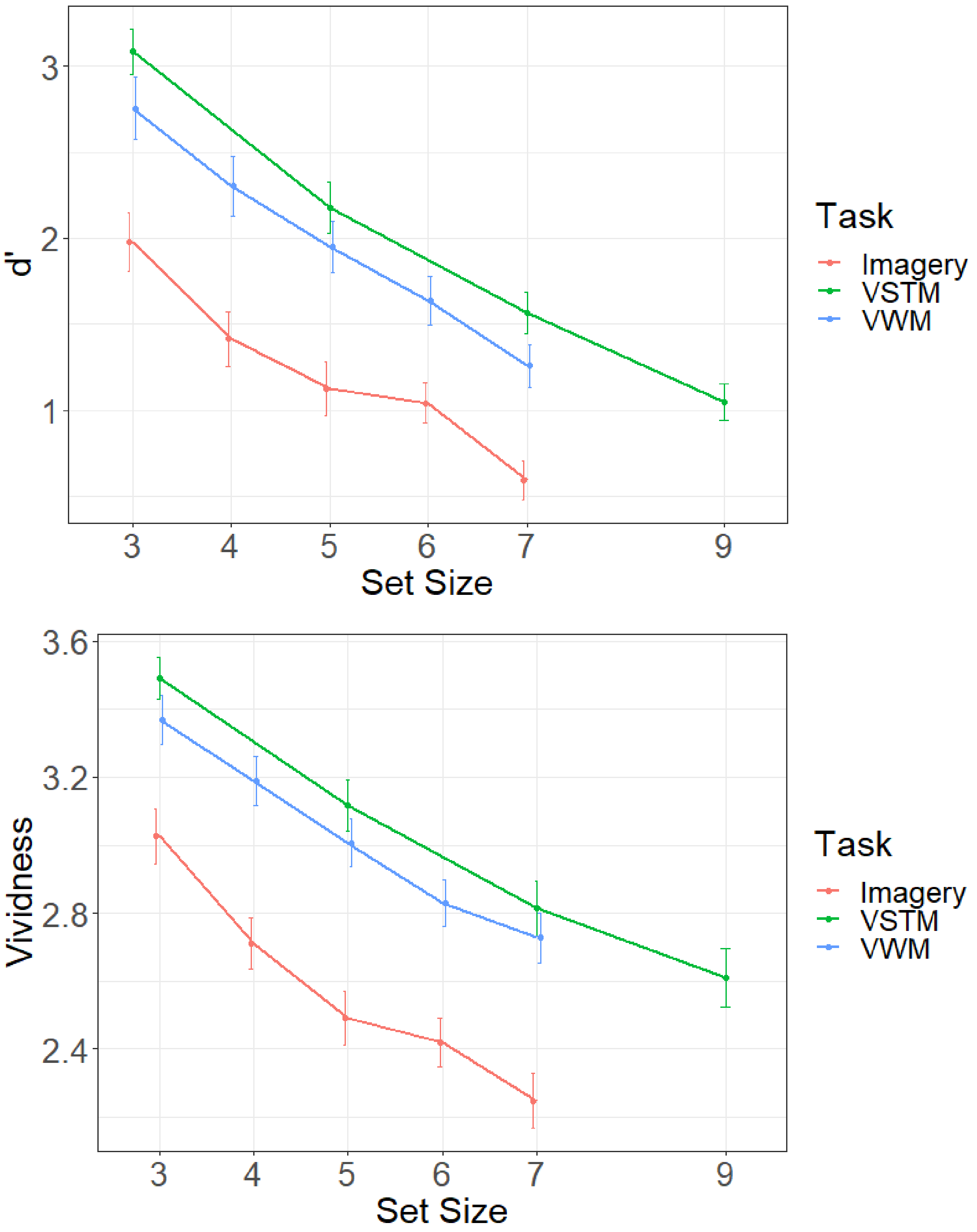

Figure 5.8. *d*' (top) and (bottom) vividness as a function of set-size for the imagery, VWM and VSTM (error bars indicate standard errors).

5.5.3.4 Imagination, VWM and VSTM results

To compare across all three tasks a 3 (task: VWM, imagination, VSTM) x 3 (set-size: 3, 5, 7) repeated-measures ANOVA on *d*' yielded an effect of task, $F(2, 82) = 46.08$, $p < .001$, $\eta_g^2 = .31$. Post hoc analysis found that VSTM performance was significantly better than imagination performance, ($p < .001$, $d = .1.13$), VWM performance was significantly better than imagination performance, ($p < .001$, $d = .1.33$), and VSTM performance was significantly better than VWM performance, ($p = .041$, $d = .40$). There was an effect of set-size, $F(2, 82) = 142.33$, $p < .001$, $\eta_g^2 = .46$, with a significant linear trend, $F(2, 27) = 53.57$, $p < .001$ signifying that as set-size increased, performance decreased approximately proportionally, and no interaction effect, $F < 1$.

A 3 (task: VWM, imagination, VSTM) x 3 (set-size: 3, 4, 7) repeated-measures ANOVA on vividness yielded an effect of task, $F(1.34, 56.86) = 35.74$ $p < .001$, $\eta_g^2 = .34$. Post hoc analysis found that VSTM vividness was significantly better than imagination vividness ($p < .001$, $d = .1.06$), VWM vividness was significantly better than imagination vividness, ($p < .001$, $d = .1.05$), and there were no significant difference between VSTM and VWM vividness, ($p = .266$, $d = .27$). There was an effect of set-size, $F(1, 41) = 136.7$, $p < .001$, $\eta_g^2 = .42$, with a significant linear trend, $F(1, 41) = 150.59$, $p < .001$ and a significant quadratic trend, $F(1, 41) = 19.17$, $p < .001$, signifying that as set-size increases, vividness scores decreased linearly at first, and then at a diminishing rate as set-size increased. There was no interaction effect between task and set-size, $F(4, 164) = 2.35$, $p = .057$, $\eta_g^2 = .01$.

5.5.3.5 VSTM results

For completeness, VSTM analysis was run separately to examine effects across all set-sizes (3, 5, 7, and 9) on *d*' and vividness. The result is a large reduction in VSTM performance and vividness as set-size increases (Figure 5.8). A repeated-measures ANOVA conducted on *d*' with set-size as a factor (3, 5, 7, 9) yielded an effect of set-size, $F(3, 123) = 96.67$, $p < .001$, $\eta_g^2 = .70$, with a significant linear trend, $F(1, 41) = 364.62$, $p < .001$ and a significant quadratic trend, $F(1, 41) = 4.62$, $p = .038$, signifying a departure from a linear trend.

A repeated-measures ANOVA was conducted on mean vividness scores with set-size as a factor (3, 5, 7, 9) yielded an effect of set-size, $F(1.88, 76.89) = 90.43$, $p < .001$, $\eta_g^2 = .69$, with a significant linear trend, $F(1, 41) = 134.93$, $p < .001$ and a significant quadratic trend, $F(1, 41) = 6.87$, $p = .012$, signifying that as set-size increased, vividness decreased at first and then tailed off as set-size increased.

5.5.3.6 Modelling procedure and Capacity Estimates

WoMMBAT (Morey & Morey, 2011) was used to model capacity of imagination and VMst (VWM and VSTM). The model is a hierarchical Bayesian extension of a non-hierarchical model developed for single-cue change detection and produces capacity estimates (*k*) for each participant (Rouder et al., 2008). The single-cue capacity model was selected as the primary model because the current study design was more similar to a single-cue design than a whole display design because the decisional processes are reduced to one item at test and thus exempts all other items on display i.e., the participant either encoded the probed item or not, which is a fundamental difference between single-cue and whole display designs (Cowan, 2001).

Data entered were trial level data on each task (imagination, VWM, VSTM), indicating the participant, set-size, whether the trial was a change trial and whether the response was correct response (whether the participant responded “change”). Two separate models were built in order to estimate capacity. The first model contained participant as a factor and the second model contained both participant and task as factors. The participant variance model contained three parameters for each participant: *k*, the number of items maintained, *z*, an attentional lapse rate, and g guessing bias (Morey, 2011). Parameters *k*, *z* and g were included with parameters *k* and *g* allowed to vary between participants. Parameter *z* was fixed for all participants (Morey, 2011). The participant variance model allowed capacity estimates to vary across participants only, not tasks. The model including participant and task as factors included five parameters for each participant with two of these parameters, *z* and *g*, being the same as above. The other three parameters were a *k* for each task (imagination, VWM and VSTM). As such this model investigated the participant by task interaction on *k*. Both models contained the default prior parameter as outline in Experiment 1.

To obtain parameter estimates the WoMMBAT model uses a Markov chain Monte Carlo (MCMC) technique. The length of the chain is controlled by a number of factors including the number of iterations (set to 100,000) and the number of burn-in iterations where a number of iterations at the beginning of the chain are discarded to minimise the influence that the first iterations can have on the chain (set to 5,000). The *hybrid Monte Carlo* parameters were set at; ε = 80, lower N_{if} = 0.015, upper N_{if} = 0.035 and are similar to the parameters used in Morey and Morey (2011). Both models used these parameters.

MCMC chain sample acceptance rates were in the range deemed to be good (between .60 and .90; Table 5.7) In addition, WoMMBAT provides a graphical method for checking the quality of the MCMC chains and thus whether they will produce good parameter estimates. For each parameter three plots are produced to assess whether the chains converge. The first is the MCMC chain plotted as a function of MCMC iteration, which should appear as random noise as is the case here (Figure 5.9). The second is the kernel density estimate which shows the marginal posterior distribution of the parameter. The third is the autocorrelation function of the MCMC chain, which for an ideal chain is 0 as it is here (Figure 5.9). Importantly the participant variance model and the participant by task model provided good MCMC chain iterations, kernel density estimates and autocorrelation functions (Figure 5.9).

The WoMMBAT fit for each model was determined by the *Deviance Information Criterion* (DIC) (lower values indicate better fit). The modelling revealed that the participant by task interaction model provided the lowest DIC, indicating that capacity differences varied between tasks (Table 5.7).

Table 5.7. Hierarchical Bayesian model fit statistics for single-cue change detection data for participant variance and participant by task (imagery, VWM and VSTM) interaction models.

Model	Number of parameters on *k*	DIC	Acceptance rate	*k*
Three levels: task type – imagery, VWM, VSTM	126	20583.7	.74	3.05 (overall) 2.16 (imagery) 3.31 (VWM) 3.69 (VSTM)
Participant variance	42	21274.7	.73	2.95

Note. *N* = 42. DIC ordered from low to high.

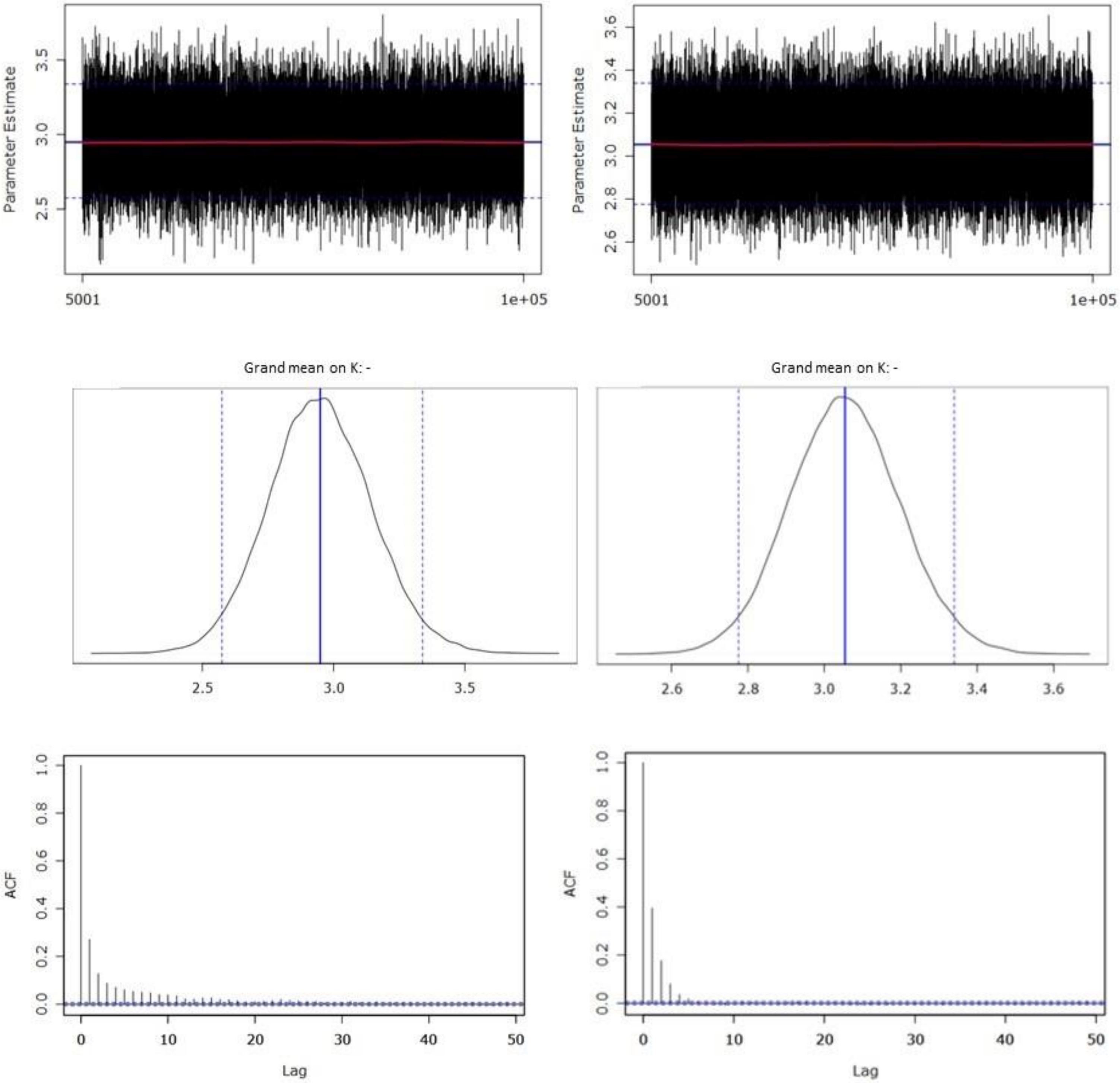

Figure 5.9. Participant variance model (left) and Participant by task model (right). MCMC chains: iterations plots (top), Kernel density plots (centre) and autocorrelations plots (bottom).

This model yielded a mean capacity (*k*) of 3.69 items in the VSTM task, 3.31 items in the VWM task and 2.16 items in the imagery task. Estimates of *k* for each participant for each task are shown in Figure 5.10. Strikingly, there was no overlap between the inter-quartile ranges of capacity estimates between imagery and VSTM, with only a small overlap between the inter-quartile ranges of imagery and VWM. A one-way repeated-measures ANOVA was conducted to compare the effect of task (imagination, VWM, VSTM) on *k*. There was a significant effect of task, $F(2, 82) = 42.05$, $p < .001$, $\eta_g^2 = .51$. Post hoc analysis found that VWM *k* was significantly higher than imagination *k* ($p < .001$, $d = 1.13$) and VSTM *k* was higher than imagination *k* ($p < .001$, $d = 1.24$), with no effect between VWM and VSTM *k* ($p = .102$, $d = .34$). Re-running the analysis but excluding participants who used a strategy yielded estimates for *k* of 3.45, 3.23 and 2.27 items in VSTM, VWM and imagination respectively.

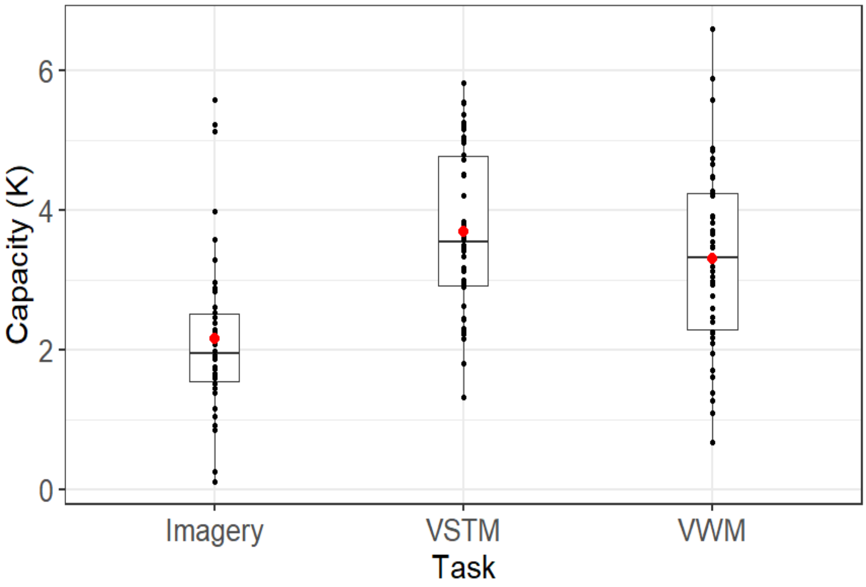

Figure 5.10. Capacity estimates (*k*) for participants in the imagery, VSTM and VWM tasks.

As briefly mentioned above, the single post-cue at test used in the current study is more similar to a single-cue design than a whole display design because the decisional processes are reduced to one item at test i.e., the participant either encoded the probed item or not, which is the fundamental difference between single-cue and whole display designs (Cowan, 2001). In whole display designs, increasing set-size necessarily increases decisional complexity as the participant has to assess whether any of the items has moved (Beck & van Lamsweerde, 2011;

Hollingworth, 2003; Luck et al., 1996). However, typically in single cue techniques only one item is shown. In this task, the aim was to reduce the influence of decisional complexity when manipulating set-size, but also to keep the test array as close to the content in memory/imagination as possible, so that a change would not disrupt performance. This meant displaying the whole display but using a single item post-cue to focus decision on one item in the display only. An argument could be made that this makes the task more like a whole display task. As such the data was also analysed using the WoMMBAT's whole display change detection model (Morey & Morey, 2011) in order to verify that the main findings were similar and as a sense check.

The same parameters were used as in Experiment 1. Each model contained 300,000 Markov Chain Monte Carlo (MCMC) samples with 5,000 burn-in iterations that converged onto the estimates. Comparable to the single-cue analysis; the model including task provided a better fit and is important in order to understand *k* differences between task (model fit statistics for all analysed models can be found in Table 5.8).

This model yielded a mean capacity (*k*) of 3.95 items in the VSTM task, 3.65 items in the VWM task and 2.69 items in the imagery task. Re-running the analysis but excluding participants who used a strategy yielded estimates for *k* of 3.75, 3.44 and 2.66 items in VSTM, VWM and imagery respectively.

Table 5.8. Hierarchical Bayesian model fit statistics for whole display change detection data for participant variance and participant by task (imagery, VWM and VSTM) interaction models.

Model	Number of parameters on *k*	DIC	Accuracy	*k*
Three levels: task type - imagination, VWM, VSTM	126	21111.4	.65	3.43 (overall) 2.69 (imagery) 3.65 (VWM) 3.95 (VSTM)
Participant variance	42	21813.3	.78	3.04

Note. *N* = 42. Model ordered from low to high DIC's.

5.5.3.7 Correlations

The means and standard deviations for the imagination strategy questions, questionnaire measures and Corsi block forward/backward tasks are reported in Table 5.9. Correlations were computed on the data of 42 participants. Table 5.10 presents correlations between imagination, VWM and VSTM capacity and performance (*d'*) with questionnaire measures. Table 5.11 shows correlations between imagination, VWM and VSTM capacity and performance (*d'*) with Corsi block forward and backward tasks. Table 5.12 presents correlations between imagination capacity, performance (*d'*) and imagination strategy questions.

As predicted, strong positive correlations were found between the three main tasks with the strongest correlation between imagery and VWM and the weakest between imagery and VSTM (Table 5.11). The same pattern was true of *d'*. This is expected given that both imagery and VWM require storage and manipulation of information and that previous research has shown similar neural activation between the tasks (Albers et al., 2013; Johnson & Johnson, 2014; Lee et al., 2012). Despite some commonality in terms of neural systems the difference in capacity between imagery and VMst may suggest some differences in underlying processes. This interpretation is supported by the findings that both Forward and Backwards Corsi span score more strongly correlated with imagery than VMst (Table 5.11). Forward and Backwards Corsi tasks have been associated with the central executive component of working memory (Smyth & Scholey, 1992; Vandierendonck et al., 2004, although see Donolato et al., 2017). Similarly, literature indicates that imagery utilises a mechanism similar to that of the central executive with top-down mechanisms assisting in creating and maintaining visual imagery (Albers et al., 2013; Dijkstra, et al., 2017). It could therefore be that the imagery and Corsi tasks recruit executive processes to a greater extent than the short-term memory tasked used here. In contrast to this finding, Experiment 1 showed no significant relationship between imagery capacity and Corsi block forward span capacity. The reasoning for this discrepancy could be due to the removed data for Experiment 1. More trials were removed at higher set-sizes (6 and 7 items) because there were fewer positions available for the allocation of cues. Previous research has suggested that at higher set-sizes the central executive is employed to support visual representation by easing cognitive load (Vandierendonck et al., 2004). It could therefore be that in Experiment 1, the imagery task did not place as much load on this central executive component due to the removal of higher set-size trials and this may be why this correlation was not seen there.

Finally, there was a significant relationship between VI capacity the strategy inventory question ‘I used numbers to help myself remember’ (Table 5.12). Indicating that using numbers to assist during the imagination task was detrimental to performance. However, it is difficult to derive conclusions from this finding because the strategy inventory question is somewhat open to participants’ interpretation. For example, participants could be using numbers to simply count the items that were appearing, or they could have used numbers as an explicit strategy to complete the task by numbering each of the squares in the grid.

Table 5.9. Descriptive results of imagination strategy questions, Corsi block forward task, Corsi block backwards task, VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

	M	*SD*
After the cues were presented, I used them as I was asked to	4.48	.51
I often *did not* imagine the objects	2.45	.89
My ability to imagine the objects were dependent on how many objects were being asked to imagine	4.48	.63
When tested I remembered the cues instead of thinking about the imagined objects	2.62	1.13
I used words and/or sentences to help myself remember	2.10	1.25
I used numbers to help myself remember	3.19	1.25
After the cues I vividly imagined the object, as if I could see it in front of me	3.36	1.06
Did the arrows make it possible for you to know which cell you were to imagine the object in?	4.14	.57
Corsi span (forward)	6.10	.96
Corsi total score (forward)	55.67	16.87
Corsi span (backward)	5.98	.92
Corsi total score (backward)	55.14	15.53
VVIQ	35.45	9.03
VOSI (Object vividness)	50.52	9.67
VOSI (Spatial vividness)	40.24	10.02
VOSI (Vividness Total)	90.76	18.52
CDQ-R interaction	22.26	5.42
CDQ-R Drama	17.57	6.41
CDQ-R maths and science	17.71	6.21
CDQ-R arts	10.38	3.51
CDQ-R Total	67.93	13.71
Mathematical proficiency	10.67	2.36

Note. *N* = 42.

Table 5.10. Correlations among imagination (Image), VWM and VSTM for *k* single-cue (S), *k* whole display (W) and *d*', and questionnaires: VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

	Image *k* (S)	VWM *k* (S)	VSTM *k* (S)	Image k (W)	VWM k (W)	VSTM k (W)	Image *d*'	WWM *d*'	VSTM d'
VVIQ	.17	.13	.06	.19	.18	.26	.13	.10	.10
VOSI (object vividness)	.16	.10	.03	.13	.04	-.09	.15	.11	.00
VOSI (spatial vividness)	.08	.05	-.02	.07	.00	-.10	.08	.09	-.02
VOSI (vividness total)	.21	.13	.07	.18	.08	-.07	.21	.13	.03
CDQ-R interaction	.29	.30	.03	.26	.29	-.03	.29	**.31***	.03
CDQ-R drama	.15	.19	-.03	.10	.15	-.11	.17	.20	-.06
CDQ-R maths and science	.21	.26	.03	.20	.30	.05	.23	.25	.02
CDQ-R arts	.17	.11	.04	.17	.08	-.06	.15	.16	.04
CDQ-R total	.22	.19	.06	.21	.23	.10	.21	.16	.07
Mathematical proficiency	.12	.08	-.02	.11	.07	.00	.09	.07	.00

Note. *N* = 42, two-tailed test; *p<.05, **p<.01.

Table 5.11. Correlations among imagination (Image), VWM and VSTM, *k* (single-cue (S), whole display (W)), performance (*d*'), forward and backwards Corsi span (CS) and forward and backwards Corsi total (CT).

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Image *k* (S)	-												
2	VWM *k* (S)	**.68****	-											
3	VSTM *k* (S)	**.47****	**.61****	-										
4	Image k (W)	**.95****	**.66****	**.45****	-									
5	VWM *k* (W)	**.68****	**.98****	**.65****	**.66****	-								
6	VSTM *k* (W)	**.48****	**.57****	**.94****	**.48****	**.61****	-							
7	Image *d*'	**.99****	**.68****	**.49****	**.94****	**.68****	**.48****	-						
8	WWM *d*'	**.67****	**.98****	**.61****	**.65****	**.95****	**.58****	**.68****	-					
9	VSTM d'	**.49****	**.62****	**.97****	**.47****	**.66****	**.92****	**.51****	**.63****	-				
10	Forward (CS)	**.46****	.23	.18	**.46****	.21	.15	**.46****	.25	.18	-			
11	Forward (CT)	**.53****	**.32***	.25	**.49****	**.31***	.2	**.54****	.31*	.26	**.96****	-		
12	Backwards (CS)	**.31***	.20	.19	.24	.22	.21	**.35***	.24	.17	**.31***	.29	-	
13	Backwards (CT)	**.49****	**.42****	**.38***	**.39***	**.42****	**.41****	**.52****	**.42****	**.37***	**.46****	**.50****	**.84****	-

Note. *N* = 42, two-tailed test; *p<.05, **p<.01.

Table 5.12. Correlations among imagination *k* and *d*’ and task strategy questions.

	Imagery *k*	Image *d*'
After the cues were presented, I used them as I was asked to	.20	.19
I often did not imagine the objects	-.06	-.11
My ability to imagine the objects were dependent on how many objects were being asked to imagine	-.07	-.08
When tested I remembered the cues instead of thinking about the imagined objects	-.13	-.15
I used words and/or sentences to help myself remember	.00	-.01
I used numbers to help myself remember	**-.31***	**-.32***
After the cues I vividly imagined the object, as if I could see it in front of me	.29	.27
Did the arrows make it possible for you to know which cell you were to imagine the object in?	-.12	-.09

Note. *N* = 42, two-tailed test; *p<.05, **p<.01.

5.5.4 General Discussion

Experiments 1 and 2 were designed to determine if the capacity of visual imagery is the same or different to that of visual memory in the short-term. A novel paradigm was developed in order to provide one of the cleanest and most direct measures of capacity for visual imagery and to be able to directly compare this with capacity in VWM by using an analogous VWM task. Experiment 2 was designed to rectify some issues in Experiment 1 that led to a ceiling effect in the VWM task. In addition, an analogous VSTM task was used to shed light on the relation between imagery and short-term visual memory tasks that require manipulation of information (VWM) or not (VSTM). As in Experiment 1, it was expected that imagery and VMst would be capacity limited with capacity of imagery being lower than that of VMst. The findings for the imagery task show similar capacity estimates to those observed in Experiment 1. This demonstrates the robustness of the utilised methods and further strengthens the argument that capacity estimates of imagery appear lower than that of VMst as measured previously (Cowan, 2001; Luck & Vogel, 1997). Critically, the estimates of capacity for the VSTM and VWM task (3-4 items) were in line with these previous capacity estimates, indicating that the lower capacity estimated for imagery was not solely a function of the specific task used here. Unlike other tasks that have been used to explore the relationship between imagery and working memory (Albers et al., 2013; Keogh & Pearson, 2017), the capacity estimates here were derived without sensory or mnemonic contamination from exposure to the to-be-imagined stimuli. Our results suggest that the capacity of imagination is severely capacity limited and is lower than the capacity in VWM/VSTM.

Why is imagery capacity lower than that of visual memory in the short-term?

In the VWM and VSTM tasks, performance may be better than imagination task because low-level sensory systems are used during encoding of the memory display. In the imagination task, this low-level sensory information is not available, and the construction of the image is instead internally generated in a top-down manner. The benefit of being able to utilise the incoming visual information for the memory tasks may aid subsequent retrieval (Cattaneo et al., 2009; Postle, 2016) as previous research has identified similar cortical activations when encoding and retrieving the same information (Nyberg et al., 2000) and related processing (see Kent et al., 2014). This explanation is aligned with that of grounded cognition, specifically the account of modal simulations (for review of grounded cognition, see Barsalou, 2008). The account of modal simulations states that experiences are re-enacted by integrating information from perception (and other modalities such as motor and introspection) to create a representation.

During re-enactment, the brain attempts to re-create the activity state it was experiencing at the time of sensory input (Barsalou 1999, Decety & Grezes 2006). It could therefore be that VWM benefits from integrating initial visual input into its representation, whereas imagery cannot benefit, due to the absence of visual input.

In addition, it is very likely that early visual cortex is activated to a lesser extent during imagery than it is during visual perception. This is consistent with the finding that imagery and perception show more similar activation the further up the visual hierarchy (Pearson, 2019; Pearson et al., 2015; see Bartolomeo et al., 2020 for discussion and Pearson, 2020 for reply to Bartolomeo et al., 2020). However, other studies have found that although the overall activation of early visual areas during imagery remains relatively low, overall pattern activity was similar between imagery, visual perception and VWM (Albers et al., 2013; Cichy et al., 2012; Lee et al., 2012). For example, a multivariate pattern classifier (MVPC) was able to decode low level features in areas V1 and V2 for both imagery and VWM stimuli, suggesting that they share a similar pattern of activation in the early occipital areas (Albers et al., 2013). In line with this is the argument that early visual areas are used as a ‘dynamic blackboard’ which can be used to form visual representations from both low-level visual input and higher-level input (Albers et al., 2013; Keogh et al., 2016). Hence, it might be that using low-level visual input when processing a representation in memory creates a stronger activation in the early visual areas in comparison to imagery due to VWM utilising both bottom-up and top-down processes. In contrast, imagery is reliant on top-down processes to create the visual representation which could create a weaker representation in the early visual areas.

The lower capacity of imagery relative to VMst might be explained by the use of separate systems. (Logie 1995, 2003, 2011; Logie & van der Meulen 2009; Pearson 2001; Quinn & McConnell, 2006). For example, Pearson (2001) suggests that imagery relies on visual buffer when generating a visual image that is separable to the subsystems proposed in memory. In contrast, perceived objects are maintained in the visual cache (Andrade et al., 2002; Cornoldi & Vecchi, 2003; Logie, 1995; 2003; 2011; Quinn & McConnell, 2006). However, Borst, Niven and Logie (2012) suggest that a visual image is later transferred from the visual buffer to the visual cache where the image is then maintained (Borst, Niven & Logie, 2012). It could be that imagery relies more on the visual buffer than VWM and this buffer might be more capacity limited than the visual cache. Interestingly, Franconeri et al. (2013) suggests that the retinotopic structure of the primary visual cortex may be responsible for capacity limitations. Therefore, it may well be that the visual buffer and the visual cache have separate capacity limits.

Another explanation for the lower capacity estimate of imagination than visual memory in the short-term could be given to the recruitment of top-down processes that enable the generation and maintenance of internally generated images (Dijkstra et al., 2017; Schlegel et al., 2013). Internally generated images produce more variable activation patterns and are less robust than activations associated with bottom-up visual mechanisms such as visual working memory (Albers et al., 2013; Pearson, 2019). These top-down processes have been associated with general attention processes (Mayer et al, 2007; Zanto et al., 2011) that have been linked to imagination (Dijkstra et al., 2017). Interestingly, Dijkstra et al. (2017) found stronger activations from top-down connections during imagery than when perceiving objects. It could be that generating and maintaining an imagined image requires more attentional process than encoding and maintaining a memory. As such, this could explain the lower capacity of imagery in comparison to VMst.

Relationship between imagery and VWM/VSTM

The strong positive relationships found between imagery and VMst support previous findings suggesting a common mechanism underpins imagery and VMst, such that imagery could support active functions of short-term visual memory (Keogh & Pearson, 2011, 2014). Area V1 in the occipital cortex has been found to be an important cortical structure in both imagery and VWM (Albers et al., 2013; Harrison & Tong, 2009; Kosslyn et al., 2001; Kosslyn & Thompson, 2003; Kosslyn et al., 1995). Crucially, VWM storage is predictive of the size of area V1, with larger surface area being associated with greater storage (Bergmann et al., 2014). Similar findings have been found in imagery research with higher spatial imagery precision associated with larger V1 surface area (Bergmann et al., 2016). These findings are consistent with research on capacity limitations in memory that propose cortical competition in early visual areas (Franconeri et al., 2013). Alvarez and Cavanagh (2004) found that higher precision and higher numbers of representations cost neural resources. Therefore, it could be that individuals with smaller V1 surface area are not able to create the precision required to maintain numerous visual representations due to the restriction on cortical resources which could reduce capacity. Whereas those with larger V1 surface area would have an increased capacity because there would be less demand within the area.

The imagery data (*d*’ and vividness) from Experiment 1 and 2 support those of Keogh and Pearson (2017), whose conclusions were drawn from a binocular rivalry task. Building on their research, the current experiment used an analogous task to measure VWM and VSTM in order to demonstrate that, although all tasks are limited in capacity, imagery capacity appears to be lower than VSTM and VWM.

Limitations

The purpose of the work reported here was to directly compare modelled capacity estimates for imagination and different short-term visual memory tasks. Whether or not these capacity estimates reflect slot based or resource-based limitations on processing is not assessed here and indeed these capacity estimates could arise from either. Whilst appearing to show that imagination capacity is reduced relative to VWM/VSTM, it is possible that alternative explanations such as presentation time, cuing methodology, and single post-cue methodology explain this difference in capacity. These alternative explanations are addressed below and in later chapters.

Imagination duration

Experiment 2 constrained the amount of time available (fixed at 2000ms per sequential presentation) to generate and perceive objects in the visual imagery and VWM tasks. It could be that this fixed duration does not enable participants to create a representation in imagination and perform memory encoding. Critically, it could be that the fixed duration disproportionally impacted visual imagery as the imagery process might be more effortful and takes longer than memory encoding. Previous research has suggested that imagery requires greater reliance on recruitment of top-down processes for the generation and maintenance of internally generated images (Dijikstra et al., 2017; Pearson, 2019; Schlegel et al., 2013). If duration was a limiting factor, then providing more time to generate and maintain an image should improve performance. Therefore, the reduced capacity of imagination relative to VWM could be due to the identical presentation times used in experiment 2.

Arrow cue methodology of the imagination task

Experiment 2 used comparable tasks to ascertain performance for imagery and VWM, so as to make the measures of capacity comparable. A 6x6 grid was presented, and in the imagination task an arrow was presented on a column and on a row, with participants having to imagine a black block at the intersection. In the working memory task, a black block was visibly presented at the location and the stimulus built up similarly with a black block being presented every 2 seconds. Although the tasks were designed to be equivalent, there is a possibility that the method used to cue the to-be-imagined black block selectively impaired imagination performance. Indeed, the cuing methodology used in the imagination task might 1) divert attention away from the to-be-imagined location and 2) increase positional noise in terms of the imagination being created at the correct location. Therefore, the arrow cues might selectively limit the performance in the imagination task.

Type of decision required

Experiment 2 used identical test displays for the imagery, VWM and VSTM tasks (e.g., participants were shown all black blocks presented with one block being highlighted white). It could be that this type of display benefited VMst performance as the stimuli were presented during build-up, which could enable configural processing, and so presenting items in their configuration at test might enhance VMst performance relative to imagination. In addition, the presentation of the black blocks in the test array may interfere with imagination processes more than VMst because these blocks were not seen during the imagination generation, whereas they were seen during build-up for VWM and VSTM. If the single post-cue methodology was a limiting factor, then investigating the importance of such factors in the test display should uncover if different test displays interfere with imagination processes more than they do for VMst. Therefore, the reduced capacity of visual imagery could be due to the test displays used in experiment 2.

These alternative explanations will be explored in the subsequent Chapters in the thesis.

Chapter 6: Experiment 3

This experiment was preregistered with the Open Science Framework: OSF Registries | The stabilisation of imagination and visual working memory

6.1 Introduction

Experiment 2 investigated the capacity limitations of imagination, visual working memory and visual short-term memory. The capacity of imagination was severely capacity limited and lower than that found in VMst. However, the previous experiments constrained the time available to participants across memory and imagination conditions. In Experiment 2, participants were asked to build up their imagination and VWM sequentially and the time for each step was fixed at 2 seconds. It may be that imagination capacity was lower because generation and maintenance of an image is more effortful and takes longer than encoding and maintaining a memory. There is substantial evidence that there is significant recruitment of top-down processes for the generation and maintenance of internally generated images (Dijikstra et al., 2017; Pearson, 2019; Schlegel et al., 2013). Indeed, Dijikstra et al. (2017) suggested that extra top-down processing resources are needed for imagery in comparison to visual perception. They found stronger top-down connectivity between the inferior frontal gyrus (IFG) and the early occipital cortex (OCC) during imagery, whereas bottom-up connectivity was found to be stronger during visual perception. IFG and OCC support VWM processes, selective attention during encoding and the maintenance of visual representations (Gazzaley & Nobre, 2012; Higo et al., 2011; Mayer et al, 2007; Nobre et al., 2004; Zanto et al., 2011). Taken together, these findings suggest that imagery could benefit from extended duration time by allowing for longer generation and maintenance of items which could lead to similar performance between the imagination and VWM tasks.

It has been found that longer presentation durations enable improved WM recall (Barrouillet et al., 2004; Brady et al., 2016; Quirk et al., 2020). Quirk et al. (2020) used a change detection task to investigate the effect of presentation time and found that extending presentation time improved memory performance. This may be explained by the effect of time on different memory-supporting mechanisms and processes, such as encoding, elaboration, refreshing and consolidation (Barrouillet et al., 2004; Bartsch et al., 2018; Vogel et al., 2006). For example, elaborative encoding increases recall performance when participants are given an increasing amount of time to maintain VWM items (Stoff & Eagle, 1971) with encoding strategies such as organisation or chunking benefiting performance (Cowan, 2001, 2005; Jiang et al., 2000).

Although, simply delaying decisions in cognitive tasks can aid performance by allowing more time for decision processes to be completed (Guest et al., 2010).

In VWM it is understood that the time available for processing and maintenance may enhance memory. One of the most prominent models describing the influence of time on memory is The Time-Based Resource-Sharing model (TBRS; Barrouillet et al., 2004; Barrouillet et al., 2007; Barrouillet et al., 2011). This model states that attention is shared between processing and maintenance of WM items with the focus of attention only being assigned to one of these functions at any one time. For a full discussion of Barrouillet et al. TBRS model see section 2.2.1.3. Critically, the TBRS model supposes that attention is shared in a time-based way with longer periods of time in which the focus of attention is not directed to a particular item harming the memory representation. However, in order to reduce time decay, attentional switching occurs between processing and maintenance at *any point in time* (Case, 1985) with more time available to refresh and restore the memory representation improving performance (Barrouillet et al., 2004; Lépine et al., 2005).

Refreshing is a process during which a representation is no longer physically present but is reactivated as a memory representation (Johnson, 1992; Johnson et al., 2002). Refreshing has been shown to be beneficial when maintaining items in VWM. For example, Souza et al. (2015) reported an advantage when items were refreshed in VWM. In Experiment 1 of Souza et al. (2015), participants were shown 6 colours and at test were asked to indicate the colour by clicking on a colour wheel. During the retention interval of the task, items were retro-cued a variable number of times (0, 1, or 2) using an arrow to cue a previously occupied location. It was found that the frequency with which an item is cued, the more likely it is to be recalled at test. In other words, items that were refreshed twice in memory were more likely to be remembered than an item that was refreshed once. In Experiment 2 of Souza et al. (2015), they used a similar method, and developed short and long duration conditions (amongst other conditions) in which no retro cues were used. Instead, the retention interval was extended from 1000ms (short condition) to 3000ms (long condition). It was found that fewer errors were made in the longer duration condition than in the shorter duration condition. This result is somewhat counterintuitive, since longer retention intervals are more commonly associated with poorer performance (e.g., King et al., 2002). However, this unusual result can be explained by refreshing, with evidence suggesting that refreshing can take place spontaneously and refreshing items for a longer duration can benefit performance (Barrouillet et al., 2004; Lépine et al., 2005; Souza et al., 2015).

Interestingly, it was found that it takes approximately 50ms to refresh one item in memory by refocusing attention on the item (Vergauwe et al., 2014). This fast refresh rate is aligned with Cowan's (2011) embedded processes model (see section 2.2.1.2 for details). Cowan (2005, 2011) states that when participants are asked to sequentially encode more than one item in memory, they are able to reactivate the previously presented items by refocusing their attention through rapid and covert retrieval processes. Furthermore, this model suggests a flexible focus of attention that can sequentially (re)activate individual items – in quick succession – by zooming-in the focus of attention on a specific item as well as zooming-out the focus of attention on numerous items (maximum 4) in memory (Cowan 2005; Cowan et al., 2007). This flexible focus of attention is supported in the literature by computational simulations (Portrat & Lemaire, 2015). According to Portrat and Lemaire (2015), the sequential nature of the focus of attention used for refreshing items is acceptable as long as there is enough time to refresh the items in memory.

Finally, consolidation time is typically measured from the onset of the stimulus and continues until attention is taken away from the memory item (Jolicoeur & Dell'Acqua, 1998; Ricker & Hardman, 2017; Wyble et al., 2011). Ricker and Cowan (2014) observed that consolidation takes approximately 300ms for the spatial location of items that rely on attention-based maintenance. Therefore, in terms of VWM, extending duration time should allow for increased refreshing and stronger memory consolidation, which should increase the strength and stability of representations, leading to better performance. It is unclear however, as to whether visual imagery will benefit from longer durations in the same way. Previously, Keogh and Pearson (2017) manipulated the duration participants had to imagine items. They found no evidence of a difference in the magnitude of effects between 6 seconds and 12 seconds, and that this was true across set-sizes, suggesting that duration is not an important aspect of imagery generation and maintenance. However, this result only suggests that there was no evidence of a difference within the 6-12 second range. There could be substantial differences in imagery when varying the time available for image generation between 0 and 6 seconds. It therefore remains important to understand if imagination is influenced by extended duration in the imagery generation stage.

The present study used the same method as Experiment 2 for imagination and visual working memory tasks. In both tasks, participants were asked to build up their working memory or imagination sequentially. The time for each step of this was manipulated (either 2 seconds or 4 seconds). In addition, set-size 4 in Experiment 2 showed the most variation across participants and so was the only set-size presented in the current study. The study aims to understand if extended presentation time improves imagination performance so that it is comparable to VWM performance. It may be that the capacity estimates differences observed between imagination and VWM in Experiment 2 were due to imagination requiring extra time to generate and maintain a visual image. Given the findings of Experiments 1-2 it is expected that performance will be better in the VWM task than the imagination task for the 2 second condition. In support of this, performance for VWM was greater than imagination performance in Experiment 2. Furthermore, it was expected that performance would be greater in the 4 second than the 2 second condition for the VWM task. This is suggested in the literature by a range of evidence that suggests that extended presentation time of information can induce memory benefits through enhancing encoding and maintenance mechanisms (Barrouillet et al., 2004; Huebner & Gegenfurtner, 2010; Lépine et al., 2005; Souza et al., 2015). In addition, if imagery generation is effortful and takes longer than 2s to create an image, it is expected that increasing the time of each step from 2-4s will improve performance. If the effort required to generate an image is responsible for the difference in capacity between VWM and imagery observed in experiments 1-2, then imagery performance in the 4s condition should approach that of the VWM task. It is not clear whether this interaction should be observed given that others have failed to find an effect of presentation time (Keogh & Pearson, 2017). Nevertheless, it is an important to rule out this potential explanation for capacity differences between VWM and imagery in experiments 1-2.

6.2 Method

6.2.1 Participants

Sample size planning was conducted using .05 (one way) significance level and was based on the 42 participants from Experiment 2 using the most relevant effect of interest (set-size 4 - imagery and VWM *d*'), effect size .82 (Cohen's d), and $r = 0.48$ (paired correlation). A priori power analysis indicated 28 participants in the current study to have a 99% power to detect such an effect. Twenty-eight participants (25 Female) took part in the experiment aged between 19 and 30 years ($M = 19.73$, $SD = 1.18$) and had normal or corrected to normal vision. The study took approximately 70 minutes to complete. Each participant received 7 research credits for taking part as a Psychology student through the Psychology Sona System. Nottingham Trent University's College Research Ethics Committee approved the study.

6.2.2 Apparatus and materials

This was the same as Experiment 2.

VVIQ

The same inventory is administered in Experiment 1. In the current study all items produce high internal reliability with Cronbach's α = .90,

VOSI

The same inventory is administered in Experiment 2. From the current study, all 14 factors produce high internal reliability with object imagery Cronbach's α = .90 and spatial imagery Cronbach's α = .86

CDQ-R

The same inventory is administered in Experiment 1. In the current study all factors produce high internal reliability with Cronbach's α > .80.

Strategy questions (Imagination)

The same questions are administered in Experiment 2.

Strategy question (VWM)

The same question is administered in Experiment 2.

Mathematical proficiency inventory

The same inventory is administered in Experiment 1. In the current study all items produce high internal reliability with Cronbach's $\alpha = .73$.

6.2.3 Design and procedure

Overview of procedure

Participants first completed the set of questionnaires as described in Experiment 2. Upon completion, the order of the imagination and VWM tasks was counterbalanced across participants anced using a Balanced Latin Square Design. Once the imagination task or VWM task was complete; questions were administered for each of these tasks which investigated the strategies used to complete the task. A repeated measures design was used.

Imagination task

The design and procedure were the same as Experiment 2, with the following exceptions. Only set-size 4 was used. In addition, each pair of arrow cues were presented for either 2 seconds or 4 seconds, depending upon the condition (duration: either 2 seconds per presentation or 4 seconds per presentation). The practice block contained 8 trials: four trials were allocated to each of the conditions (duration: either 2 seconds or 4 seconds) and of the four trials two was allocated to the "same" test array presentation and two to the "different" test array presentation. Each of the two trials were either presented to the left or right of the display. Three equally balanced main blocks comprised 72 trials. Each duration therefore comprised 36 trials, 18 "same" trials and 18 "different" trials of which 9 were presented to the left and 9 presented to the right of the display. All trials were randomised.

VWM task

The design and procedure were the same as Experiment 2, with the same alterations as presented in the above design section for imagination.

6.3 Results

6.3.1 Data preparation

The data preparation was the same as Experiment 2.

6.3.2 Statistical analysis

A 2 (task: VWM, imagination) x 2 (duration: 2 second, 4 second) repeated measures analysis of variance (ANOVA) was carried out on performance (*d*') and vividness ratings in 2 separate ANOVAs. The main analysis included all participant data. Three participants reported using alternative cognitive strategies (e.g., 'I gave each black block a specific number to encode its location'). Statistical analysis was re-conducted with these participants removed. Since no evidence of a difference was found, only the main analysis is reported.

6.3.3 Imagination and VWM results

The means and standard deviations for proportion correct for each task and duration are shown in Table 6.1. Figure 6.1 clearly shows a large reduction in *d*' for imagination in comparison to VWM performance, but within each task, duration had minimal effect on performance. A 2 (task: imagination, VWM) x 2 (presentation time: 2 seconds, 4 seconds) repeated measures ANOVA was conducted on *d*'. There was a significant effect of task with performance better for VWM than imagination, $F(1, 27) = 131.83$, $p < .001$, $\eta_g^2 = .60$. There was no significant differences found between presentation time, $F < 1$, and no significant interaction effect, $F(1, 27) = 1.47$, $p = .236$, $\eta_g^2 = .02$.

Table 6.1. Mean and standard deviations (parenthesis) for proportion correct for task (imagination and VWM) across duration (two, four seconds).

	Imagination		VWM	
Presentation time (Seconds)	Two	Four	Two	Four
Proportion correct	.76 (.11)	.76 (.10)	.91 (.08)	.90 (.09)

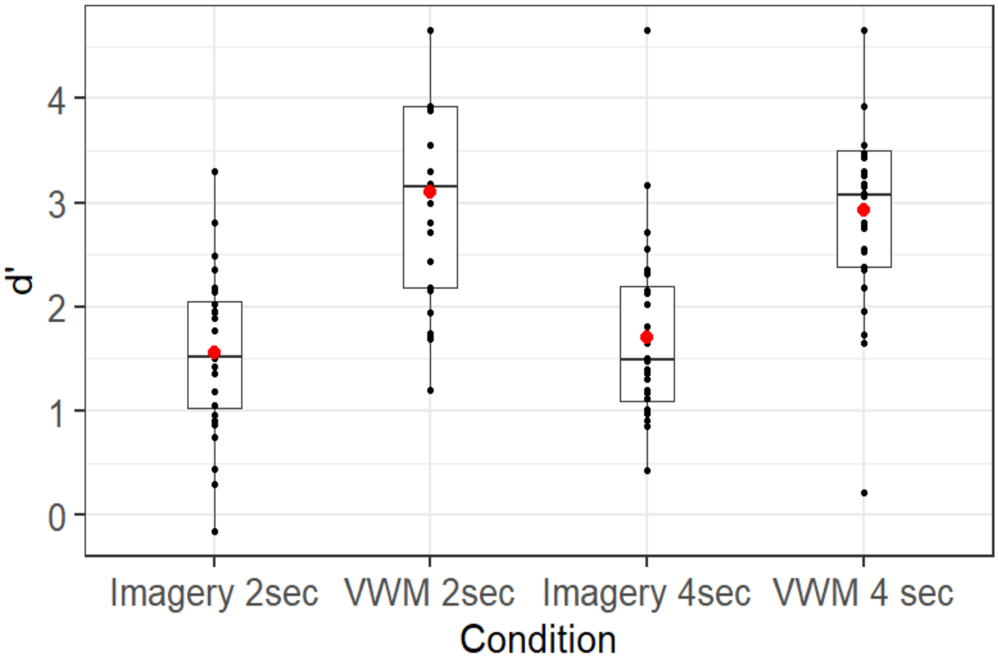

Figure 6.1. *d*' for presentation time (2 and 4 seconds) for each task (imagery and VWM). Error bars indicate standard errors.

In Figure 6.2, mean imagery vividness is shown for each presentation time and task. There is a reduction in vividness for imagination in comparison to VWM. However, only VWM vividness appeared influenced by presentation time with lower vividness ratings for the 4 second than the 2 second condition. A 2 (task: imagination, VWM) x 2 (presentation time: 2 seconds, 4 seconds) repeated measures ANOVA was conducted on mean imagery vividness. For presentation time there was a significant effect of task with VWM performance producing higher vividness scores than imagination, $F(1, 27) = 76.78$, $p < .001$, $\eta_g^2 = .66$. There was no significant differences found between presentation time, $F<1$, but there was a significant interaction effect, $F(1, 27) = 6.10$, $p = .020$, $\eta_g^2 = .03$. Post hoc analysis showed no significant effect of presentation time on imagination, t (28) = 1.26, $p = .219$, $d = .24$, but there was a significant effect of presentation time on VWM, with higher vividness scores observed in the 2s compared to the 4s condition, t (28) = 2.30, $p = .029$, $d = .43$.

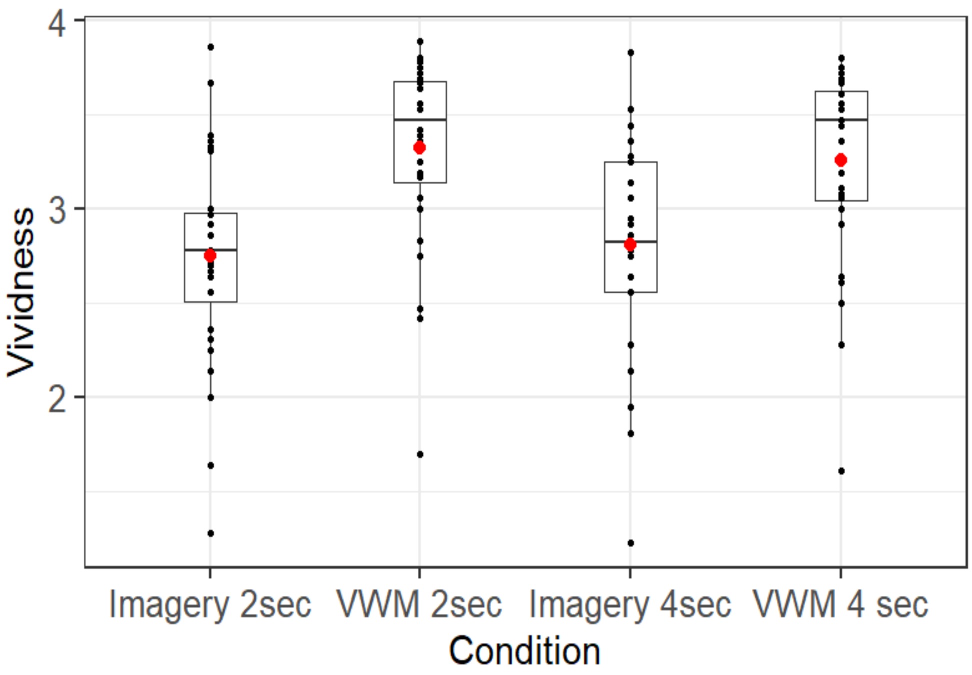

Figure 6.2. Mean vividness score for presentation time (2 and 4 seconds) for each task (imagination and VWM). Error bars indicate standard errors.

6.3.4 Correlations

The means and standard deviations for the imagination strategy questions and questionnaire measures are reported in Table 6.2. Table 6.3 shows correlations between imagination and visual working memory (2 seconds and 4 seconds) performance (*d*') and questionnaire measures. Table 6.4 presents correlations between imagination performance (*d*') and strategy questions.

Strong positive correlations were found between between imagination and VWM (see Table 6.3). This is consistent with imagination and VWM sharing similar processes and potentially sharing neural networks and corroborates the findings from Experiment 2. There were no significant correlations between imagination performance and questionnaire measures and no significant correlations between VWM performance and questionnaire measures (see Table 6.3). In addition, there were no significant correlations found between imagination performance and task strategy (see Table 6.4). These results are broadly consistent with the findings from Experiment 1 and 2.

Table 6.2. Descriptive results of strategy questions (imagination), VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

	M	*SD*
After the cues were presented, I used them as I was asked to	4.25	0.44
I often did not imagine the objects	2.54	0.88
When tested I remembered the cues instead of thinking about the imagined objects	2.46	1.14
I used words and/or sentences to help myself remember	2.36	1.34
I used numbers to help myself remember	2.89	1.42
After the cues I vividly imagined the object, as if I could see it in front of me	3.57	0.88
Did the arrows make it possible for you to know which cell you were to imagine the object in?	4.00	1.05
VVIQ	37.00	10.32
VOSI (Object vividness)	46.00	8.64
VOSI (Spatial vividness)	37.64	9.85
VOSI (Vividness Total)	83.64	16.92
CDQ-R interaction	24.29	5.05
CDQ-R Drama	17.82	5.63
CDQ-R maths and science	17.96	4.88
CDQ-R arts	11.18	3.45
CDQ-R Total	71.25	13.30
Mathematical proficiency	11.82	2.07

Note. *N* = 28.

Table 6.3. Correlations among imagination and VWM *d*' (combined 2 and 4 second conditions for each task) and questionnaires: VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

		1	2	3	4	5	6	7	8	9	10	11	12
1	Imagination	-											
2	VWM	**.70****	-										
3	VVIQ	.06	.12	-									
4	VOSI (Object vividness)	-.07	-.03	**-.82****	-								
5	VOSI (Spatial vividness)	.00	-.09	**-.69****	**.68****	-							
6	VOSI (Vividness Total)	-.04	-.06	**-.82****	**.90****	**.93****	-						
7	CDQ-R interaction	.01	-.20	**-.47***	.33	**.41***	**.41***	-					
8	CDQ-R drama	-.11	-.06	**-.43***	.35	.25	.33	**.41***	-				
9	CDQ-R maths and science	.17	-.25	-.30	.13	.17	.16	**.50****	.13	-			
10	CDQ-R arts	-.21	-.01	-.34	.29	.17	.25	**.38***	**.49****	-.08	-		
11	CDQ-R total	-.04	-.19	**-.56****	**.40***	.37	**.42***	**.83****	**.75****	**.59****	**.58****	-	
12	Mathematical proficiency	.28	-.10	-.17	.13	.33	.26	**.38***	.07	**.39***	-.11	.29	-

Note. *N* =28, two-tailed test; * *p* <.05, ** *p* <.01.

Table 6.4. Correlations among imagination (combined 2 and 4 second conditions) and task strategy questions.

		1	2	3	4	5	6	7	8
1	Imagination	-							
2	After the cues were presented I used them as I was asked to	-.24	-						
3	I often did not imagine the objects	-.05	-.17	-					
4	When tested I remembered the arrows instead of thinking about the imagined objects	-.19	.18	-.04	-				
5	I used words and/or sentences to help myself remember	-.07	**.28**	-.04	.15	-			
6	I used numbers to help myself remember	.04	-.07	-.10	-.01	.35	-		
7	After the cues I vividly imagined the object, as if I could see it in front of me	-.06	**.38***	-.17	-**.42***	.14	-.22	-	
8	Did the arrows make it possible for you to know which cell you were to imagine the object in?	.10	-.08	-.24	-.06	-.08	-.22	.16	-

Note. *N* = 28.

6.4 Discussion

The study aimed to understand if extended presentation time improves imagination performance so that it is comparable to VWM performance. If so, this would indicate that the capacity differences observed between imagination and VWM in Experiment 2 were due to imagination requiring extra time to generate and maintain a visual image. This experiment therefore manipulated the time in each stage of the sequential build of the stimulus (presentation time of 2s or 4s) whereas this was 2s in experiment 1-2. It was expected that performance would be better in the VWM task than the imagination task for the 2 second condition. It was also expected that performance would be greater in the 4 second than the 2 second condition for the VWM task. Furthermore, it was expected that if generation was effortful and required more time then performance in the 4 second condition in the imagination task should approach performance in the VWM task. The findings of Experiment 3 however show that the time available to imagine objects did not affect performance. Rather, performance differences remained stable between the tasks at 2s and 4s presentation time. It can therefore be argued that the capacity differences found between imagination and VWM in Experiment 2 cannot be explained by imagination needing more time to be able to generate and maintain items.

Why did presentation time not improve performance in the VWM or imagery tasks?

Previous research found that internally generated images have a greater reliance on top-down processes than images that are externally perceived (Dijikstra et al., 2017; Pearson, 2019; Schlegel et al., 2013). Internally generated images produce more variable activation patterns and are less robust than activations associated with bottom-up visual input in tasks such as in visual working memory (Albers et al., 2013), and this greater variability may underlie the lower imagery capacity observed in experiments 1-2 relative to VWM capacity. Despite the increased reliance on top-down processing in visual imagery compared to visual perception (Dijkstra et al., 2017; Nobre et al., 2004), which may potentially take time to have its full effect, there was no effect of increasing imagination cue duration. Although Keogh and Pearson (2017) reported that increasing imagery generation time from 6 – 12 seconds did not improve priming in the binocular rivalry task, 6 seconds is significantly longer than the 2 second presentation time used in experiments 1-2 and so it could have been that generation had not been fully completed within this time window. The results of Experiment 3 however suggest that the time needed to effectively generate an image is less than 2 seconds. Indeed, evidence suggests that imagery generation occurs within 1 second (Pearson et al., 2008). Therefore, the extra time did not help because enough time had already passed such that imagination performance had built up to its maximum (i.e., there was no room for improvement).

Similar to imagery, VWM was not affected by extended presentation time. This contrasts with previous research that found that longer durations improved WM (Barrouillet et al., 2004; Brady et al., 2016; Lépine et al., 2005; Quirk et al., 2020). For example, Quirk et al. (2020) found the VWM performance increased with additional encoding time (200ms-2000ms). The discrepancy between the findings could be explained by the presentation of information. Quirk et al. (2020) presented items simultaneously, whereas the current experiment presented items sequentially. Previous evidence suggests that sequentially presented stimuli are potentially encoded more quickly and relatively automatically compared to simultaneously presented stimuli (Bharti, et al., 2020). It could therefore be that extended presentation time only benefits simultaneously presented stimuli as more time is needed to encode multiple stimuli at once, whereas with sequentially presented stimuli, only a single additional item is to be encoded.

By contrast, the current experiment supports previous literature that did not show an improvement in performance with increased encoding time (Alvarez & Cavanagh, 2008; Vogel et al., 2006). The lack of effect of extended presentation time in the current experiment may be due to the presentation time exceeding consolidation time. The consolidation of items in memory is estimated to take between 50ms and 500ms depending on factors such as stimulus complexity (Alvarez & Cavanagh, 2008; Jolicœur & Dell'Acqua, 1998; Nieuwenstein & Wyble, 2014; Ricker & Cowan, 2014; Vogel et al., 2006). Therefore, it could be argued that extending presentation time from 2000ms to 4000ms in the current experiment had no effect because 2000ms was enough time to consolidate items in memory.

Another explanation for the lack of effect of extended presentation time on VWM could be around refreshing opportunities. Souza et al. (2015) found that increasing the frequency of retro-cues in retention intervals improved performance as these prompted participants to refresh items in memory. In contrast, the current experiment did not provide explicit refreshing prompts, however participants could spontaneously refresh items in memory given the extended duration. Souza et al. (2015) suggested that participants could spontaneously refresh memory items as removing the retro cues and extending the retention interval from 1000ms to 3000ms led to a decrease in errors. An alternative explanation of Souza et al's. (2015) finding is that the delay improved performance by allowing more time for decision processes to complete (Guest et al., 2010). In the current experiment, it seems likely that participants were focusing on encoding the stimuli rather than spontaneously refreshing items or any other type of rehearsal (Bartsch et al., 2018).

Interestingly, the Time-Based Resource-Sharing (TBRS; Barrouillet et al., 2004) suggests that extending presentation time could improve performance because it allows time for switching between processing and maintenance of the stimuli which minimises time-related decay. The findings here did not support this model. However, in many of the studies that investigate this model, presentation time rarely goes above 2000ms (e.g., Puma et al., 2018; Vergauwe & Cowan, 2015) and so, the lack of support here could be due to the current VWM task using presentation times that go beyond the time usually used. The findings here rather suggest that 2000ms was enough time to support memory mechanisms and processes.

The performance and vividness differences found between imagination and VWM corroborate with the findings of Experiment 2. However, there was tentative evidence that VWM vividness was lower in the 4 second condition than the 2 second condition. Although, it is not fully clear why this occurred. It could be that vividness is reduced in a time-based manner such that over longer durations the vividness of the visual representation reduces.

Limitation

It could be that only using one set-size (4) in the current study influenced performance. In Experiment 2, set-size was manipulated (3-7) in each task in order to estimate capacity. Performance in Experiment 2 (set-size 4) was lower than was found in the current experiment. A reason for this could be that when the succession of stimuli is list-like then items cannot be grouped as effectively and this can affect performance (Cowan, 2001). It may well be that ambiguity around the length of items presented in a trial, such as in Experiment 2, affected performance more than when the length of a list is known, such as in the current experiment. Therefore, in the current experiment, it could be argued that items were assigned to a relative position because there was no ambiguity in how many items were to be presented during each trial.

Chapter 7: Experiment 4

This experiment was preregistered with the Open Science Framework: OSF Registries | Does cueing methodology selectively constrain imagination performance in comparison to visual working memory

7.1 Introduction

Experiment 3 investigated how imagination and VWM performance is influenced by extended presentation time (2 seconds versus 4 seconds). It was reasoned that imagination might require additional time to generate and maintain an image in comparsion to VWM. However, the results indicated that presentation time had no effect on performance in either imagination or VWM. Nevertheless, significant differences remained between the two tasks with VWM performance better than imagery performance. Therefore, it might be that other methodological factors selectively limit the performance in the imagination task but not the VWM task.

Another factor that might have selectively impaired imagination performance is the specific choice of cueing methodology. In the imagination task the cues were outside the grid and thus more peripheral than in the VWM condition, in which the items were simply presented at the grid location. This may have two effects. First, it may divert attention away from the location at which the imagined stimulus is being visualised. If attention is required to maintain such a visualisation, then this would hinder performance. Second, it may increase the noise in terms of the imagination being created at the precise location. Thus, the cues might act to increase variability in terms of the location of the imagination. Indeed, Borst and Kosslyn (2010) created a spatial imagery task for location using an arrow cue to determine if imagined dots were in a specific location. They found that the error rate increased as the distance between cue and test location increased. Furthermore, Bergmann et al. (2016) found similar effects using the binocular rivalry paradigm (see section 2.1.3 for detailed description of binocular rivalry paradigm) such that, priming effects at peripheral locations were significantly lower than priming effects at central locations. Similarly, subjective vividness ratings were significantly lower at peripheral locations than at central locations. Taken together, these results suggest that increasing the distance between cue and location may impact imagery negatively. This could be due to the dispersion of attention. As attentional allocation is dispersed over greater distance and places, then the ability to allocate attention to a specific location decreases due to diverting attention outside the area of focus (Eriksen & St. James, 1986). Furthermore, increased noise in an imagination could be due to the arrow cues increasing binding errors as neighbouring locations to the cued location could be wrongly selected.

It is widely accepted that VWM and attention are highly related processes (Chun et al., 2011; Close et al., 2014; Theeuwes et al., 2011) with many theories accounting for attention based working memory (for a review, see Cowan, 2017). Plentiful research has demonstrated that attending to a particular object or location improves the transfer of information into VWM (Cowan & Morey, 2006; Schmidt et al., 2002; Vogel et al., 2005). Furthermore, allocating attention to neighbouring target objects in visual space in comparison to non-neighbouring target objects has been found to improve VWM performance (Abbes et al., 2014). Indeed, attention is better allocated to one spatial area than to several spatial areas (Heinze et al., 1994; McCormick & Klein, 1990; Posner et al., 1980) with divided attention studies finding improved performance when items are presented in close proximity (Hoffman et al., 1985; Hoffman & Nelson, 1981; Kramer et al., 1985). These findings suggest that attention is restricted by spatial proximity, with the allocation of attention being more difficult when objects are presented in a larger spatial area. Therefore, VWM performance could be affected by the size of the spatial area when allocating attention. In terms of the current paradigm, arrow cues in the imagination task may increase the size of the space needing to be attended, reducing performance.

Another contributing factor to VWM capacity is the number of possible locations within a memory array (Philips, 1974; Vecchi et al., 1995). For example, Cornoldi et al. (1991) manipulated the complexity of a set of grids and found that participants produced more errors in a spatial pathway task when the grid contained 64 (8 x 8) locations than when the grid contained 16 (4 x 4) locations. The reasoning for these results could be two-fold. One reason is that as the number of possible locations increase, the opportunity to commit an error also increases due to the increase in decisions (Lappin & Uttal, 1976; Palmer et al., 1993). In other words, there are more decisions to be made about a cued location when there are 64 possible locations than when there are 16 locations. Another reason is that the increase in possible locations is simply an increase in the number of potential distractor locations. Interestingly, the presence of distractors has been found to decrease VWM performance (Fukuda & Vogel, 2009; McNab & Klingberg, 2008). This creates competition between distractor and target locations within perceptual systems or memory systems as they compete for a limited resource (Franconeri et al., 2013).

The impact of increasing possible locations and increasing proximity has been found to reduce performance (Eriksen & Hoffman, 1972; Burkell & Pylyshyn, 1997). Franconeri et al. (2007) used a visual search task and manipulated both set-size and the number of possible locations to see how many locations could be selected. It was found that participants were more accurate with sparse (12 possible locations) than dense (24 possible locations) displays and also the effect of set-size was greater in the dense than sparse display. Indeed, when distancing between items was dense participants could only select approximately 2-3 locations. However, when distancing between items was sparse participants could select 6-7 locations. These results suggest a trade-off between possible locations and spatial proximity. That is, increasing possible locations within an array (and thus reducing spatial proximity) decreases memory performance. The effects could be due to the focus of attention not being able to provide the level of precision needed to select a cued location among distractors with attention selecting neighbouring locations alongside the to-be-selected location (Souza et al., 2018).

The present study used the same methodology as Experiment 2 for imagination and VWM. In both the imagination and VWM tasks, participants were asked to build up their imagination or VWM sequentially. Although the tasks were designed to be equivalent, there is a possibility that the method used to cue the to-be-imagined black block selectively impaired imagination performance. In the imagination task the cues were outside the grid and thus more peripheral than in the VWM condition, in which the items were simply presented at the grid location. The aim of this study was to explore the extent to which the arrow cues in the imagination task diverted attention away from the to-be-imagined location and increased noise in the cued location.

The experiment manipulated the size of the global grid (small or large) and the number of locations in the grid (4 x 4 or 6 x 6). Decreasing the global grid size of the grid but maintaining the same number of locations increases the density of the grid. Therefore, the number of locations was also manipulated orthogonally. The large global grid size and 6 x 6 locations for imagination and VWM tasks were used previously in Experiments 2 and 3 and are therefore replications. It is hypothesised that decreasing global grid size (small compared to large) will improve performance as it has been suggested that it is easier to allocate attention in a smaller scale of space (Abbes et al., 2014; Eriksen & St. James, 1986; Hoffman et al., 1985; Hoffman & Nelson, 1981; Kramer et al., 1985). In particular, if the difference observed between imagination and VWM performance in Experiment 2 was due to the cues directing attention away from the to-be-imagined object, then decreasing the global grid size, and thus decreasing the absolute distance of the cue from the to-be-imagined object, should improve performance in the imagination task (Bergmann, et al., 2016; Borst & Kosslyn, 2010) more than the VWM task. Decreasing the number of locations (4 x 4 compared to 6 x 6) will lead to increased performance because it will reduce decision making (Lappin & Uttal, 1976; Palmer et al., 1993) and location uncertainty (Fukuda & Vogel, 2009; McNab & Klingberg, 2008). In particular, if the difference observed between imagination and VWM performance in Experiment 2 was due to the cues in the imagination condition increasing noise in the visualised object, then reducing the number of locations should increase imagination performance more than VWM performance. There should also be an interaction between the global grid size manipulation and the number of locations such that the effect of increasing the number of locations will be greater when the global grid size is small. This is because reducing the size of the global grid but maintaining the same number of locations will reduce the size of each spatial location. This creates a denser display that could make it harder to spatially locate the imagined or memorised objects (Franconeri et al., 2007; Souza et al., 2018). Furthermore, if the cues in the imagination task act to increase noise in the visualised object, then this interaction should be greater in the imagination task than the VWM task.

To assess the impact of the arrow cue in the periphery, the cue location (near or far) and the number of locations (4 x 4, 6 x 6) was manipulated in the imagination task. Note that the cue location cannot be manipulated in the VWM task as the task does not use arrows to cue location. The near cue location 4 x 4 and 6 x 6 are repetitions from the conditions presented above (Figure 7.1: panels A and C). The two new conditions are far cue location 4 x 4 and 6 x 6 (Figure 7.1: panels I and J). The far cue location presents the arrow cues in the same locations as if the global grid size was large. These two conditions therefore extend the distance from the arrow cues to the to-be-imagined locations. The aim of adding these conditions is to understand if diverting attention further away from the imagined location hinders performance. It is hypothesised that increasing the distance of cues from the grid in the imagination task will decrease accuracy because it will increase the absolute distance between cues and the to-be-imagined object (Bergmann et al., 2016; Borst & Kosslyn, 2010) This is because attention will be further dispersed from the area of focus (Eriksen & St. James, 1986).

Finally, to investigate if arrow cues draw attention away from location, a condition was included that assessed the impact of arrow cues on VWM performance. In this condition, a large global grid size and 6 x 6 locations was used with arrow cues being presented simultaneously with the build-up of the black blocks (Figure 7.1: panel K). This will be compared with the large global grid size and 6 x 6 location VWM condition (Figure 7.1: panel F). This will show whether the arrow cues direct attention away from areas in the grid. It is expected that simultaneously presenting arrow cues and a black block during build-up may decrease accuracy in the VWM task, if arrow cues divert attention away from location.

Furthermore, given the results of the previous experiments, it is expected that performance in the imagination and VWM tasks will positively correlate.

7.2 Method

7.2.1 Participants

Sample size planning was conducted using .05 (one way) significance level and was based on the 42 participants from Experiment 2 using the most relevant effect of interest (set-size 5 - imagery and VWM *d*'), effect size .79 (Cohen's d), and $r = 0.52$ (paired correlation). A priori power analysis indicated 32 participants in the current study to have a 99% power to detect such an effect. Thirty-two participants (22 Female) took part in the experiment aged between 19 and 31 years ($M = 22.3$, $SD = 4.4$) and had normal or corrected to normal vision. The study took approximately 180 minutes to complete. Each participant received 18 research credits for taking part as a Psychology student through the Psychology Sona System. Nottingham Trent University's College Research Ethics Committee approved the study.

7.2.2 Apparatus and materials

This was the same as Experiment 2.

VVIQ

The same inventory is administered in experiment 1. In the current study, all items produce high internal reliability with Cronbach's $\alpha = .85$.

VOSI

The same inventory is administered in experiment 2. From the current study, all factors produce high internal reliability with object imagery Cronbach's $\alpha = .90$ and spatial imagery Cronbach's $\alpha = .86$.

CDQ-R

The same inventory is administered in Experiment 1. In the current study all factors produce high internal reliability with Cronbach's $\alpha > .82$.

Strategy questions (imagination)

The same questions are administered in experiment 2 with the addition of two extra questions. Question 1) 'Did less grid locations (i.e., 16 instead of 36) assist in reducing uncertainty as to which location was being cued by the arrows?’ Question 2) ‘When arrow cues were positioned further away from the grid did this make it more difficult to imagine the black block?’ Each question was rated on a 5-point Likert-style scale that ranges from 1 ’fully disagree’ to 5 ‘fully agree’.

Strategy question (VWM).

The same question is administered in experiment 2.

Mathematical proficiency inventory

The same inventory is administered in Experiment 1. In the current study all items produce high internal reliability with Cronbach’s $\alpha = .87$.

7.2.3 Design and procedure

Overview of procedure

Participants first completed the set of questionnaires as described in Experiment 2. Upon completion, participants completed 11 different experimental conditions (for details of each condition, Figure 7.1). Conditions were counterbalanced using a Balanced Latin Squared Design. A repeated measures design was used. Once all the imagination or VWM tasks were complete; questions were administered for each of the tasks which investigated the strategies used to complete the task.

Imagination task

The design and procedure were the same as experiment 2, with the following exceptions. Experiment 2 manipulated set-size, only a set-size of 5 will be used here, as the focus of the tasks is not on set-size effects but on how methodological differences could alter performance in the memory and imagination tasks. The 2 (global grid size: small, large) x 2 (number of locations: 4 x 4, 6 x 6) corresponds to small global grid size and 6 x 6 grid locations (Figure 7.1: panel A), large global grid size and 6x6 grid locations (Figure 7.1: panel B), small global grid size and 4 x 4 grid locations (Figure 7.1: panel C), and large global grid size and 4x4 grid locations (Figure 7.1: panel D). The large global grid size and 6 x 6 locations is the same condition that has been used throughout the thesis. The grid measured 6.72 cm x 6.72 cm and consisted of 36 squares with each square measuring 1.12 cm x 1.12 cm. The line width on the outer edge of the grid was .20 cm and between each square was a line width of .20cm (the line width is the same in each condition). The large global grid size and 4 x 4 locations consisted of a grid that measured 6.72 cm x 6.72 cm and consisted of 16 squares with each square measuring 1.68 cm x 1.68 cm. The small global grid size and 6 x 6 locations consisted of a grid that measured 4.48 cm x 4.48 cm and consisted of 36 squares with each square measuring .75 cm x .75 cm. The small global grid size and 4 x 4 locations consisted of a grid that measured 4.48 cm x 4.48 cm and consisted of 16 squares with each square measuring 1.12 cm x 1.12 cm. The arrow cues in all these conditions are placed at the top of a column and the left side of a row indicating that a block should be imagined at the intersection of that column and row (Figure 7.1: panel A-D).

The 2 (cue location: near, far) x 2 (number of locations: 4 x 4, 6 x 6) all use small global grid size and corresponds to 6 x 6 grid locations with far arrow cues (Figure 7.1: panel I), 4 x 4 grid locations with far arrow cues (Figure 7.1: panel J), 6 x 6 grid locations with near arrow cue (Figure 7.1: panel A) and 4 x 4 grid locations with near arrow cue (Figure 7.1: panel C). The arrow cues for the near cue location conditions are presented on the outer edge of the grid. In contrast, the arrow cues in the far cue location conditions (panel I and J in Figure 7.1) are placed as if a large global grid size is being presented (as in Figure 7.1: panel B and D).

Each condition had a practice block and a main block. The practice block contained 4 trials: 2 were allocated to the “same” test array presentation and 2 to the “different” test array presentation. 1 of the “same” trials and 1 of the “different” trials were presented to the left of the display the other “same” and “different” trials were presented to the right of the display. The main block contained 36 trials. 18 “same” trials and 18 “different” trials of which 9 of each were presented to the left and 9 of each were presented to the right of the display. All trials were randomised.

VWM task

The design and procedure were the same as experiment 2, with the same 2 (global grid size: large, small) x 2 (number of locations: 6 x 6, 4 x 4; Figure 7.1: panel E-H) alterations as presented in the above imagination design section. In addition, the condition that simultaneously presented arrow cues and black block, presented arrows on the outer edge of the large global grid size, one aligned with a randomly selected column, and the other with a randomly selected row (Figure 7.1: panel K). Arrow cue size and colour were the same as used in the other imagination conditions. The black blocks were presented at location as used in the other VWM conditions. This meant that both the arrows and a black block were cuing the same specific location.

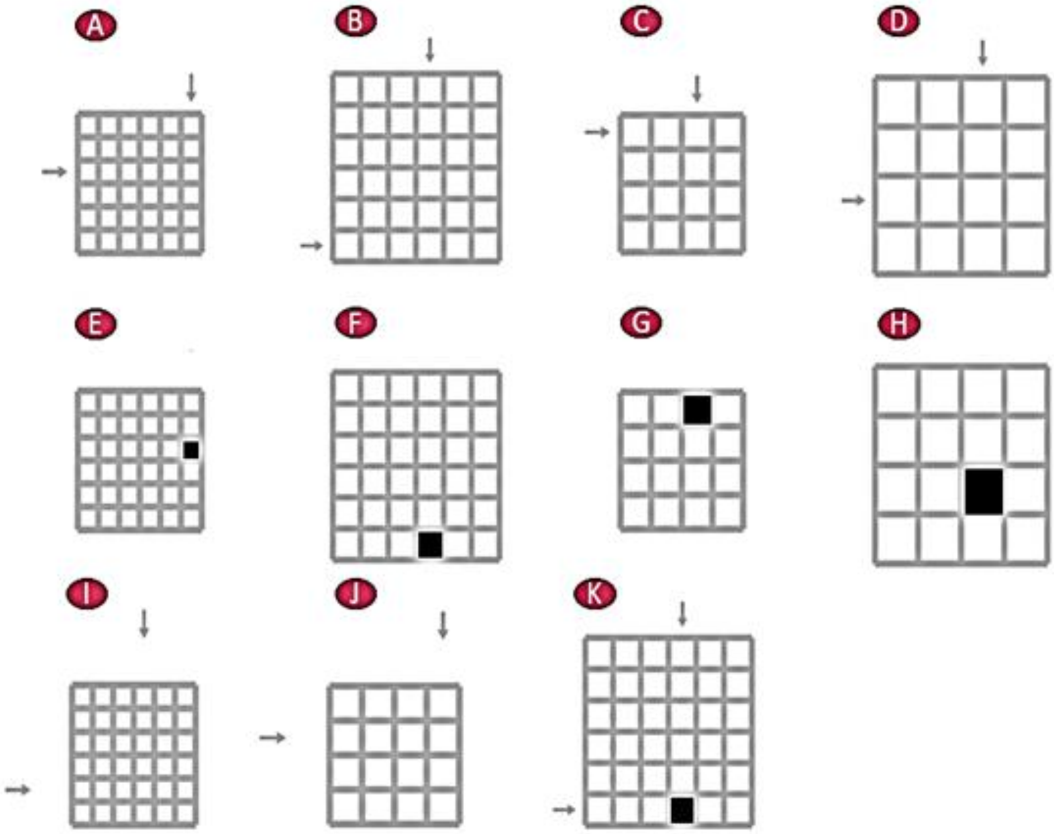

Figure 7.1. A single sample display presentation for each of the 11 conditions. Imagination conditions are represented by panel A-D and panel I-J. VWM conditions are represented by panel E-H and panel K. Panel A and E represents small global grid size and 6 x 6 grid locations, panel B and F represents large global grid size and 6 x 6 grid locations, panel C and G represents small global grid size and 4x4 grid locations, panel D and H represent large global grid size and 4 x 4 grid locations, panel I represent small global grid size and 6 x 6 grid locations with far arrow cues and panel J represents small global grid size and 4 x 4 grid locations with far arrow cues. Panel A and C represent the near arrow cue conditions. Panel K represents VWM plus arrows and is comparable to panel F with the inclusion of the arrow cues. In the imagination task - participants were asked to create black block in their minds eye at the intersections of the pairs of arrows whereas in the VWM task, blocks were visibly presented in the display.

7.3 Results

7.3.1 Data preparation

The data preparation was the same as Experiment 2. The main analysis included all participant data. Three participants reported using alternative cognitive strategies (e.g., ‘I gave each black block a specific number to encode its location’). Statistical analysis was re-conducted with these participants removed. Since no evidence of a difference was found, only the main analysis is reported.

7.3.2 Statistical analysis

A 2 (task: imagination, VWM) x 2 (global grid size: large, small) x 2 (number of locations: 4 x 4, 6 x 6) repeated measures analysis of variance (ANOVA) was carried out on performance (*d*’) and vividness ratings in 2 separate ANOVAs. In addition, A 2 (cue location: near, far) x 2 (number of locations; 4 x 4, 6 x 6) repeated measures ANOVA was carried out on performance (*d*’) and vividness ratings for the imagination task in 2 separate ANOVAs. Finally, a paired *t* test was carried out on the large global grid size and 6 x 6 number of locations VWM condition and large global grid size and 6 x 6 number of locations with arrow cues VWM condition on performance (*d*’) and vividness ratings.

7.3.3 Imagination and VWM results

The means and standard deviations for proportion correct for global grid size and number of locations are shown in Table 7.1 for imagination and VWM. There is a large reduction in *d*’ (and proportion correct) for imagination in comparison to VWM performance with global grid size having a minimal effect on performance in both imagination and VWM, whereas fewer grid locations improved both imagination and VWM (Figure 7.2). A 2 (task: imagination, VWM) x 2 (number of locations: 6 x 6, 4 x 4) x 2 (global grid size: large, small) repeated measures ANOVA was conducted on *d*’ values. There was a significant effect of task with VWM performance producing better scores than imagination, $F(1, 31) = 39.87$, $p < .001$, $\eta_g^2 = .22$, and a significant effect of number of locations with fewer locations (4 x 4) performance producing better scores than greater locations (6 x 6), $F(1, 31) = 86.4$, $p < .001$, $\eta_g^2 = .22$. There was no significant effect of global grid size, $F < 1$ and no significant interaction effects; task and number of locations, $F < 1$, task and global grid size, $F(1, 31) = 3.2$, $p = .083$, $\eta_g^2 <$

.01, number of locations and global grid size, *F*(1, 31) = 2.9, *p* = .099, $\eta_g^2 < .01$, and no significant three way interaction effect, *F*(1, 31) = 2.7, *p* = .111, $\eta_g^2 < .01$.

Table 7.1. Mean and standard deviations (parenthesis) for proportion correct for task (imagination, VWM) across global grid size (large, small) and grid locations (6 x 6, 4 x 4).

	Imagination				VWM			
Global grid size	Large	Small	Large	Small	Large	Small	Large	Small
Grid locations	6 x 6	6 x 6	4 x 4	4 x 4	6 x 6	6 x 6	4 x 4	4 x 4
Overall	.67 (.13)	.69 (.12)	.79 (.16)	.79 (.14)	.82 (.15)	.78 (.14)	.88 (.15)	.88 (.15)

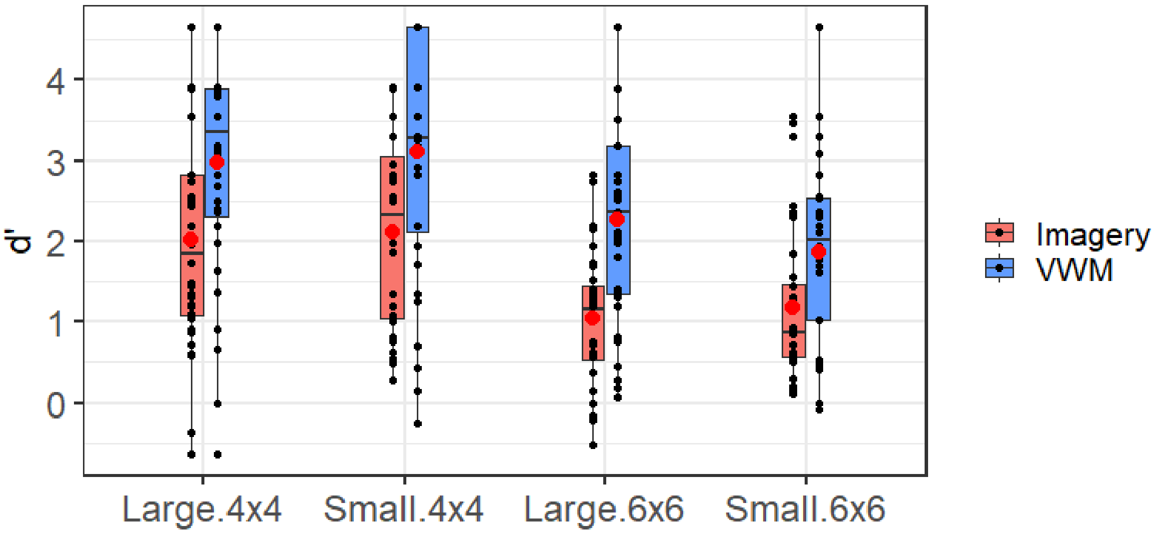

Figure 7.2. *d'* for number of locations (4 x 4, 6 x 6) and global grid size (small, large) in each task (imagery and VWM).

In Figure 7.3, mean imagery vividness scores can be seen for grid locations (4 x 4, 6 x 6) and global grid size (small, large) for imagery and VWM. There is a reduction in vividness for imagination in comparison to VWM with global grid size having a minimal effect on performance in both tasks, whereas fewer grid locations improved both imagination and VWM vividness. A 2 (task: imagination, VWM) x 2 (number of locations: 4 x 4, 6 x 6) x 2 (global grid size: large, small) repeated measures ANOVA was conducted on averaged imagery vividness. There was a significant effect of task with VWM performance producing better vividness scores than imagination, $F(1, 31) = 64.21$, $p < .001$, $\eta_g^2 = .26$. and a significant effect of number of locations with fewer locations (4 x 4) producing better vividness scores than greater locations (6 x 6), $F(1, 31) = 26.01$, $p < .001$, $\eta_g^2 = .17$. There was no significant effect of global grid size, $F < 1$ and no significant interaction effects; task and number of locations, $F(1, 31) = 1.67$, $p = .205$, $\eta_g^2 < .01$. task and global grid size, $F(1, 31) = 1.88$, $p = .180$, $\eta_g^2 < .01$. number of locations and global grid size, $F < 1$, and no significant three-way interaction effect, $F < 1$.

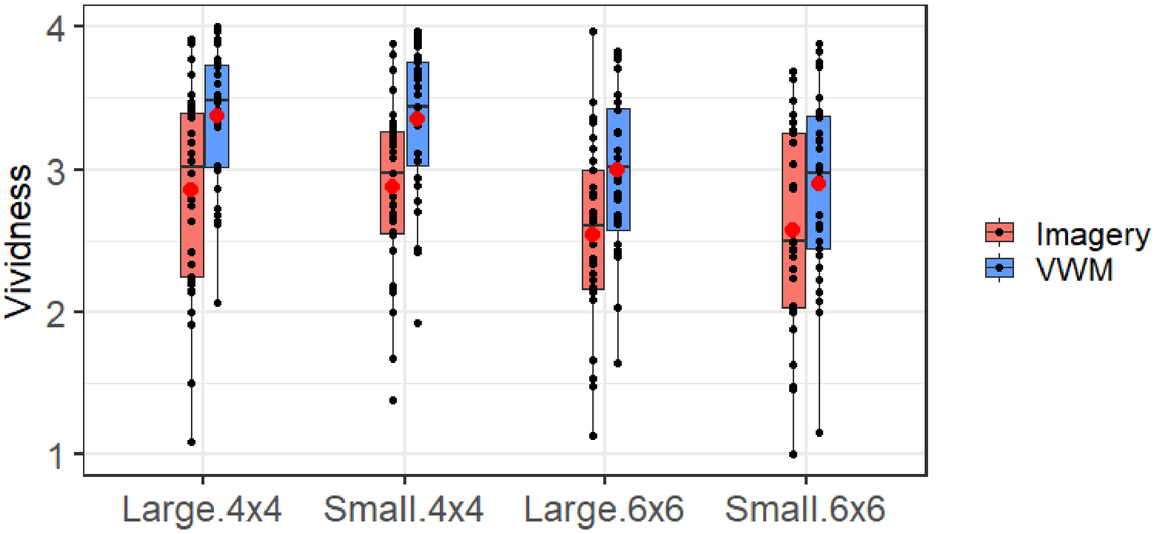

Figure 7.3. Mean vividness scores for number of locations (4 x 4, 6 x 6) and global grid size (small, large) in each task (imagery and VWM).

7.3.4 Imagination - cue location results

The means and standard deviations for proportion correct for cue location (far, near) and number of locations (4 x 4, 6 x 6) are shown in Table 7.2 for imagination, with *d'* shown in Figure 7.4. Although the number of grid locations appeared to influence *d*', the location of the cue did not (Figure 7.4). A 2 (cue location; far, near) x 2 (number of locations: 4 x 4, 6 x 6) repeated measures ANOVA was conducted on *d*' values (performance). There was a significant effect of number of locations with performance improved when there were fewer grid locations, $F(1, 31) = 43.05$, $p < .001$, $\eta_g^2 = .37$. The was no main effect of cue location, $F(1, 31) = 2.87$, $p = .101$, $\eta_g^2 = .02$, and no significant interaction effect, $F < 1$.

Table 7.2. Mean and standard deviations (parenthesis) for proportion correct for number of locations (6x6, 4x4) and cue location (far, near) in the imagination task.

	Imagination			
Number of locations	6 x 6	6 x 6	4 x 4	4 x 4
Cue location	Far	Near	Far	Near
Overall	.67 (.15)	.69 (.12)	.79 (.14)	.79 (.14)

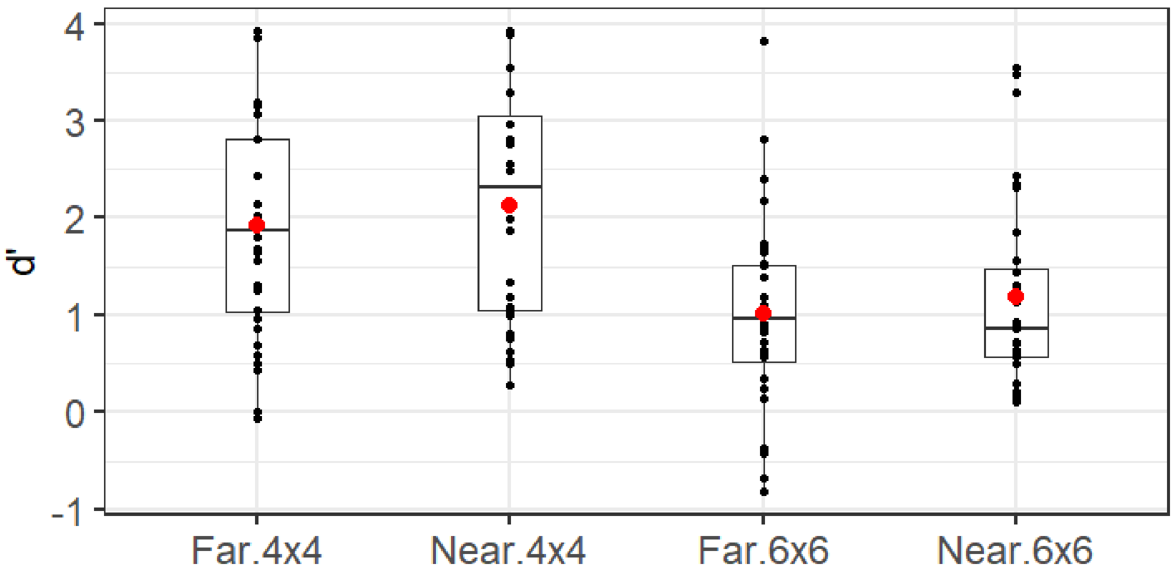

Figure 7.4. *d*’ for number of locations (4 x 4, 6 x 6) and cue location (far, near) in the imagination task.

A 2 (cue location: near or far) x 2 (number of locations: 6 x 6, 4 x 4) repeated measures ANOVA was conducted on averaged imagery vividness There is a reduction in vividness for 6 x 6 locations in comparison to 4 x4 locations near cue benefiting 6 x 6 location vividness and far cue benefiting 4 x 4 location vividness (Figure 7.5). There was a significant effect of number of locations with 4 x 4 number of locations producing better vividness scores than 6 x 6 number of locations, *F*(1, 31) = 34.06, *p* < .001, η_g^2 = .33. There was no significant effect of cue location, *F*<1. There was a significant interaction effect between the number of locations and cue location, *F*(1, 31) = 5.23, *p* = .028, η_g^2 = .05. Post hoc analysis found that far cue with 4 x 4 locations produced significantly better vividness scores than far cue with 6 x 6 locations, *t* (31) = 6.36, *p* <.001, *d* = .83, near cue with 4 x 4 locations produced significantly better vividness scores than near cue with 6 x 6 locations, *t* (31) = 3.01, *p* = .005, *d* = .82. There was marginally significant effect of near cue with 6 x 6 locations producing better vividness scores than far cue with 6 x 6 locations, *t* (31) = 2.05, *p* = .049, *d* = .36. Finally, there was no significant effect between near cue and 4 x 4 locations and far cue with 4 x 4 locations, *t* (31) = 1.27, *p* = .214, *d* = .22.

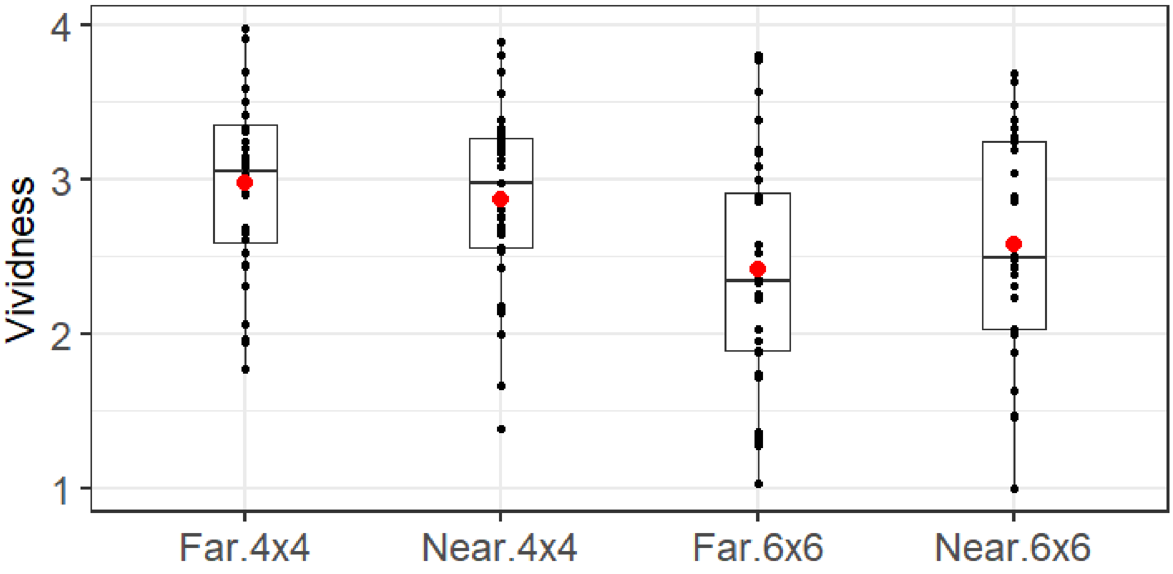

Figure 7.5. Mean vividness score for number of locations (4 x 4, 6 x 6) and cue location (far, near) in the imagination task.

7.3.5 VWM task with arrow cues results

A paired *t* test was conducted to compare performance (*d*') (Figure 7.6) and averaged vividness scores (Figure 7.7) on large global grid size with 6 x 6 number of locations and large global grid size with 6 x 6 number of locations with arrows (see Table 7.3 for means and standard deviations on proportion correct). There were no significant differences between large global grid size with 6 x 6 number of locations and large global grid size with 6 x 6 number of locations that presented arrow cues, *t* (31) = 1.26, *p* = .218, *d* = .22, and no significant effect on averaged vividness scores, *t* (31) = 1.49, *p* = .146, *d* = .26.

Table 7.3. Mean and standard deviations (parenthesis) for proportion correct for VWM and VWM with arrow cues.

	VWM	VWM (with arrow cues)
Overall	.82 (.15)	.81 (.16)

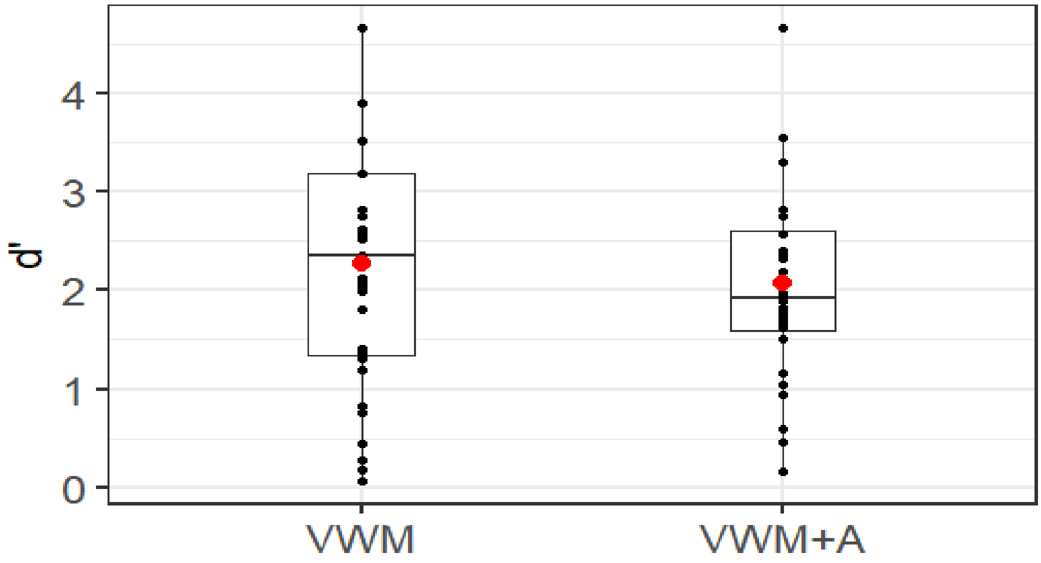

Figure 7.6. d’ for VWM and VWM with arrow cues (VWM+A).

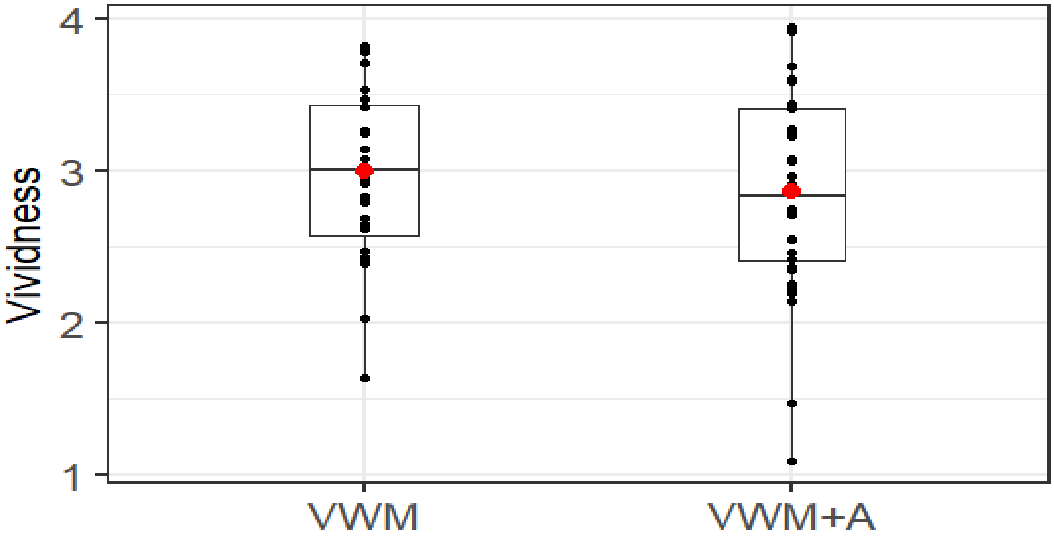

Figure 7.7. Mean vividness score for VWM and VWM with arrow cues (VWM+A).

7.3.6 Correlations

The means and standard deviations for the imagination strategy questions and questionnaire measures are reported in Table 7.4. Correlations were computed on the data of 32 participants. Table 7.5 shows correlations between imagination *d*' and VWM *d*' with questionnaires. Table 8 presents correlations between imagination *d*' and imagination strategy questions.

As predicted, strong positive correlations were found between imagery and VWM *d'* (see Table 7.5) and is consistent with the findings of the previous experiments. This is expected given that both imagery and VWM require storage and manipulation of information and that previous research has shown similar neural activation between the tasks (Albers et al., 2013; Johnson & Johnson, 2014; Lee et al., 2012). Interestingly, a strong positive correlation was found between object vividness in the VOSI and VWM *d*' (see Table 7.5), but this relationship was not found in any other previous experiments in this thesis. Therefore, it is not clear why the relationship exists. Similar to the finding in Experiment 1, an association was found between mathematical proficiency and imagination *d'* (see Table 7.5). Limited research has investigated the link between imagination and mathematical proficiency, with Abrahamson (2006) calling research into the mechanisms and agency of imagination in mathematical reasoning. Finally, there was a significant negative relationship between imagination *d*' and the strategy questions 'I often did not imagine the objects' and 'When tested I remembered the cues instead of thinking about the imagined objects' (see Table 7.6). This suggests that not imagining the objects and remembering the arrow cues instead of imagining the objects may be detrimental to performance. This provides evidence for the validity of the imagination task.

Table 7.4. Descriptive results of imagination strategy questions, VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

	M	*SD*
After the cues were presented, I used them as I was asked to	4.28	.46
I often did not imagine the objects	2.53	1.02
When tested I remembered the cues instead of thinking about the imagined objects	2.00	1.02
I used words and/or sentences to help myself remember	2.22	1.41
I used numbers to help myself remember	2.91	1.38
After the cues I vividly imagined the object, as if I could see it in front of me	3.56	0.80
Did the arrows make it possible for you to know which cell you were to imagine the object in?	3.88	1.01
Did less grid locations (i.e., 16 instead of 36) assist in reducing uncertainty as to which location was being cued by the arrows?	4.31	0.78
When arrow cues were positioned further away from the grid did this make it more difficult to imagine the black block?	3.78	1.16
VVIQ	36.59	6.21
VOSI (Object vividness)	49.53	6.05
VOSI (Spatial vividness)	38.41	8.34
VOSI (Vividness Total)	87.94	12.78
CDQ-R interaction	23.34	4.16
CDQ-R Drama	19.41	4.95
CDQ-R maths and science	17.69	4.39
CDQ-R arts	11.44	2.49
CDQ-R Total	71.88	9.33
Mathematical proficiency	10.91	1.96

Note. *N* = 32.

Table 7.5. Correlations among imagination and VWM *d’* (number of locations: 6x6, 4x4 and global grid size: large, small) and questionnaires: VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Imagery large 6x6 *d'*	-																	
2	Imagery small 6x6 *d'*	**.68****	-																
3	Imagery large 4x4 *d'*	**.56****	**.55****	-															
4	Imagery small 4x4 *d'*	**.55****	**.65****	**.69****	-														
5	VWM large 6x6 *d'*	**.49****	**.69****	**.60****	**.59****	-													
6	VWM small 6x6 *d'*	**.55****	**.59****	**.65****	**.59****	**.74****	-												
7	VWM large 4x4 *d'*	**.52****	**.36***	**.41***	**.45***	**.63****	**.63****	-											
8	VWM small 4x4 *d'*	**.47***	**.49****	**.38***	**.50****	**.73****	**.64****	**.80****	-										
9	VVIQ	-.27	-.30	-.22	-.07	-.25	-.27	-.10	-.16	-									
10	VOSI (Object vividness)	.13	.28	.15	.20	**.49****	.27	**.38***	**.51****	**-.62****	-								
11	VOSI (Spatial vividness)	-.10	.13	-.08	.04	.03	-.03	-.01	.04	**-.57****	**.57****	-							
12	VOSI (Vividness Total)	.00	.22	.02	.12	.25	.11	.17	.27	**-.66****	**.84****	**.92****	-						
13	CDQ-R interaction	-.17	-.24	-.01	-.23	-.04	.01	-.12	-.17	.08	.06	-.03	.01	-					
14	CDQ-R Drama	-.24	-.05	-.22	-.31	-.06	-.07	-.18	-.07	-.15	.11	.21	.19	.19	-				
15	CDQ-R maths and science	.17	.18	.06	.27	-.14	.00	-.10	.03	-.01	.03	**.37***	.26	.07	-.11	-			
16	CDQ-R arts	-.03	-.09	-.17	-.07	-.08	-.08	-.24	-.07	.02	.04	-.11	-.05	.31	.27	.05	-		
17	CDQ-R Total	-.13	-.07	-.14	-.16	-.14	-.06	-.26	-.12	-.05	.11	.24	.21	**.66****	**.64****	**.46****	**.57****	-	
18	Mathematical proficiency	**.36***	**.42***	**.40***	**.42***	.17	.33	.18	.33	-.07	.21	.16	.21	.17	-.24	**.58****	-.08	.20	-

Note. *N* = 32, two-tailed test; *p<.05, **p<.01.

Table 7.6. Correlations among imagination *d*' (all 6 imagination conditions combined) and task questions.

		1	2	3	4	5	6	7	8	9	10
1	*d*'	-									
2	After the cues were presented, I used them as I was asked to	.01	-								
3	I often did not imagine the objects	**-.44***	-.12	-							
4	When tested I remembered the cues instead of thinking about the imagined objects	**-.62****	.14	.31	-						
5	I used words and/or sentences to help myself remember	.02	-.05	.30	.09	-					
6	I used numbers to help myself remember	-.08	-.01	.13	.05	.31	-				
7	After the cues I vividly imagined the object, as if I could see it in front of me	.34	.35	-.10	-.16	.03	.28	-			
8	Did the arrows make it possible for you to know which cell you were to imagine the object in?	.07	.22	.13	-.06	-.07	-.06	.33	-		
9	Did less grid locations (i.e. 16 instead of 36) assist in reducing uncertainty as to which location was being cued by the arrows?	.31	.20	-.22	-.33	-.04	-.06	.23	.01	-	
10	When arrow cues were positioned further away from the grid did this make it more difficult to imagine the black block?	.10	.24	-.06	-.08	.15	.15	.03	-.14	**.36***	-

Note. *N* = 32, two-tailed test; *p<.05, **p<.01.

7.4 Discussion

The study was designed to determine if the poorer performance in the imagination task relative to the VWM task in experiment 2 was due to the cueing methodology. In the imagination task of experiment 2, the cues were outside the grid and thus more peripheral than in the VWM condition, in which the items were simply presented at the grid location. The arrow cues may therefore have diverted attention away from the to-be-imagined location and increased noise as to where the cued location was. To investigate this, the current experiment manipulated the global grid size (large, small) and the number of locations (4 x 4 , 6 x 6) in each task (imagination, VWM). It was expected that if the difference observed between imagination and VWM performance in experiment 2 was due to the cues directing attention away from the to-be-imagined object and / or increasing noise in the visualised object, then reducing the grid size and increasing the number of locations should reduce performance in the imagination task more than VWM. In addition, the current experiment manipulated arrow cue location (near, far) in the imagination task. It was anticipated that reducing the distance between the arrow cues and the to-be-imagined location should improve imagination performance in comparison to when the arrow cues are further away from the to-be-imagined object. Finally, it was expected that simultaneously presenting arrow cues and a black block should reduce VWM performance if arrow cues draw attention away from the to-be-remembered object.

The results of the current experiment show imagery performance (*d*') was lower than VWM in all comparable conditions. There was no main effect of global grid size. There was a main effect of number of locations, with fewer locations improving performance similarly in both tasks. Critically, there were no statistically significant interaction effects. No effect of arrow cue location (far or near) on imagery performance and no effect of introducing arrow cues on the VWM task was detected. Taken together these findings suggest that imagery performance is poorer than VWM, but this does not appear to be due to the cueing methodology in the imagery task diverting attention away from the cued locations nor is it due to increased noise knowing where to generate the image (the cued location). Therefore, the cuing methodology did not selectively impair the imagery task.

Number of locations and grid size

The main effect of number of locations was found for both imagery and VWM performance similarly. This was expected given that VWM literature shows an improvement in performance with reduced locations (Cornoldi et al., 1991; Philips, 1974; Vecchi et al., 1995). The reasoning for improved performance in imagery when reducing the number of possible locations could be due to there being less noise surrounding the correct location of the to-be imagined / remembered object, which could therefore decrease the potential of committing errors (Lappin & Uttal, 1976; Palmer et al., 1993). An alternative explanation for this effect could be due to the reduction in potential distractor locations. Fukuda and Vogel (2009) found that distractors reduced performance in VWM. Furthermore, they argue that being able to selectively attend to a relevant location is important for VWM capacity. In the current study, the reduction in the number of locations potentially reduces the conflict between cued and non-cued locations and therefore improves the ability to attend to the correct location.

Arrow cue location in imagination

There was no evidence that increasing the cue distance from the grid decreased accuracy. It was suggested that attention would be dispersed due to the increased distance between the arrow cues and the to-be-imagined item. This lack of effect suggests that the distance from the arrow cues to the point of imagination is not an important factor. Furthermore, there was no evidence that simultaneously presenting arrow cues and a black block decreased VWM accuracy. If the arrow cues did draw attention away from the to-be-remembered object, then performance might be expected to decrease. In combination, these null findings support the idea that the arrow cues did not divert attention away from the to-be-imagined or to-be-remembered location.

Interestingly, the lack of effect on cue location in the current study does not replicate previous findings. Borst and Kosslyn (2010) developed a spatial imagery task that used an arrow cue to determine if imagined dots were in a specific location. They found that increasing the distance between the arrow cue and test location increased errors. Similarly, Bergmann et al. (2016) found reduced priming in the subsequent binocular rivalry when participants were imagining items at peripheral locations in comparison to central locations. Bergmann et al.’s findings suggest that increasing the distance between cue and the point of imagination reduces performance. However, the differences between the current experiment and Bergmann et al. (2016) findings could be explained by different methodological approaches. For example, Borst and Kosslyn (2010) required participants to study a pattern of dots and then draw them on paper from memory. It would be fair to state that this method is indicative of memory rather than imagery as participants are remembering the previously viewed dots rather than self-generating the image. In contrast, the method used in the current study requires self-generation of objects. It is therefore a purer measure of imagery as it is not contaminated by sensory information. In contrast, Bergmann et al.'s (2016) location-specific imagery precision task establishes an indirect measure of imagery *strength* as it provides a measure of priming between the imagined object and the perceptual rivalry. The arrow cues used in the current study enable the build-up of imagination online and so allows for a more direct test of what is being imagined.

The current study found a marginal significant interaction effect of vividness on cue location and number of locations, such that 6 x 6 locations near cue vividness was better than 6 x 6 far cue location. However, this was a weak effect, and the lack of equivalent finding in the *d*' data provides robust evidence against the idea that the arrow cues diverted attention away from the point of imagination. Caution should be taken therefore with interpreting what this means.

The purpose of this experiment was to determine whether aspects of the visual arrangements of the stimuli impacted on imagery performance more than VWM in Experiment 2. The results clearly show that none of these factors are sufficient to explain why imagery performance is substantially lower than VWM in Experiment 2. It could therefore be that other factors could explain the difference in performance between imagery and VWM and this will be investigated in subsequent chapters.

Chapter 8: Experiment 5

This experiment was preregistered with the Open Science Framework: OSF Registries | The configuration of imagination and visual memory

8.1 Introduction

Experiment 3 and 4 investigated if methodological factors underpinned the capacity differences found between imagination and VWM in Experiment 2. The results showed that duration (Experiment 3) and cueing methodology (Experiment 4) were not driving the capacity differences found between imagination and VWM in Experiment 2. An alternative possibility is that it is the way in which items are presented at test that hinders imagination performance in comparison to VMst. In Experiment 2, the test display contained all the items that should have been in memory or imagination. A post-cue identified a single item, and participants judged if that item was in the same/different location relative to what was previously presented or imagined. It may be that this form of test display benefited VMst because presenting the stimuli visually in the VWM and VSTM tasks enabled configural processing, and so presenting items in their configuration at test may have enhanced performance in these conditions relative to the imagination condition. Additionally, the presentation of the black blocks in the test array may disrupt imagination processes more than VMst because these blocks were not seen during imagination generation, whereas they were seen during the sample array for VWM and VSTM. Indeed, it is possible that imagination representations are more fragile because they have been generated in a top-down manner only and thus may lack the fidelity of item representations where there has been sensory input from the display (Albers et al., 2013; Dijikstra et al., 2017; Pearson, 2019). This might mean that any interference caused by the test display is particularly detrimental for imagination.

The extent to which presenting items at test may systematically impact imagery or memory tasks may also depend on the underlying architecture of these systems. Some authors propose separate cognitive systems between imagery and VM (Logie 1995, 2003, 2011; Logie & van der Meulen 2009; Pearson 2001; Quinn & McConnell, 2006). According to this view, imagery relies on a visual buffer when generating a mental image (Logie, 2003; Kosslyn & Thompson, 2003; Pearson, 2001; Quinn and McConnell, 2006) and is situated in the early visual areas (Ganis et al., 2009; Kosslyn, 1994; Kosslyn et al., 1993; Kosslyn et al., 2006; Kosslyn & Thompson, 2003). According to this view, visually perceived objects are retained in a passive store (the visual cache) which are protected from perceptual interference (Andrade et al., 2002;

Borst, Niven & Logie, 2012) and is situated in the posterior parietal cortex (Todd & Marois, 2004, 2005). In support of this view, behavioural studies provide evidence of separable cognitive systems between imagery and VWM. For example, irrelevant visual input has been found to disrupt image generation but does not disrupt image retention (Borst, Niven & Logie, 2012). Furthermore, van der Meulen et al. (2009) found that imagery and VWM were sensitive to different types of interference. VWM retention was affected by spatial tapping but not by irrelevant pictures. In contrast, imagery *generation* was affected by irrelevant pictures, but was not affected by spatial tapping. The double dissociation suggests that 1) the process underlying imagery generation is separate to that of short-term visual retention, and 2) imagery generation is disrupted by visual content whereas VMst is not. Therefore, if imagery is generated by a separate system (i.e., the visual buffer) to that of VMst (i.e., the visual cache), then presenting all black blocks at test could selectively interfere with the imagery system, which could potentially reduce the capacity of imagery in comparison to that of VMst.

It is not yet known how imagery relies on spatially related information, and if imagery encodes items independently or in relation to each other. In contrast, research has extensively investigated how visual memory encodes items spatial information. Jiang et al. (2000) investigated VSTM using a change detection paradigm. They varied the test array in order to understand how information is encoded in VSTM and found that VSTM is organised by global spatial relations. This finding supports the *relational encoding hypothesis* which states that presented items are inter-related and encoded together e.g., the cup was on the saucer (Alvarez, 2011). However, Jiang et al.'s (2000) design only used simultaneous presentation of information. It could be that the encoding of simultaneous information is different to encoding sequential information. Indeed, Yamamoto and Shelton (2009) presented objects simultaneously (8 objects together), sequentially (4 objects followed by a further 4 objects) and repeated (8 objects presented twice) and found better memory performance for the sequential and repeated conditions than the simultaneous condition, suggesting that sequential information is encoded differently to that of simultaneous information. This provides evidence for the *independent encoding hypothesis* which states that individual items are encoded separately, and items are not interdependent (Woodman et al, 2012) and contrasts with that of the *relational encoding hypothesis* (Alvarez, 2011). However, it could be argued that the sequential and repeated conditions in Yamamoto and Shelton's (2009) study were not representative of sequential presentation. For example, they presented 4 objects and a further 4 objects in only two presentations in the sequential condition. It could be that by presenting 4 objects at a time, participants were able to form representations of spatial relations between the objects, which strengthen the visual representation. It is therefore possible that the sequential condition used similar processes to that of the simultaneous condition. In contrast, Blalock and Clegg (2010) presented individual items in a sequential manner. They studied how encoding of simultaneous and sequential memory arrays alter performance in a series of different test arrays. Participants were presented with simultaneous and sequential sample arrays and were tested under 4 spatial configuration conditions: no change (same items in the same location), new configuration (entirely new array), array shift (items have the same spatial organisation but the absolute position of the array has moved) and item switch (two items exchange places). Importantly, the array shift condition tested relational encoding and the item switch condition tested independent encoding. They found that capacity was higher in the simultaneous presentation than the sequential presentation. Crucially, both simultaneous and sequential presentation performance was lower in the item switch condition than any other condition. These findings illustrate that irrespective of encoding presentation (simultaneous or sequential) the configuration of VMst is based on a global configuration representation and therefore provide further support for the *relational encoding hypothesis* (Alvarez, 2011). However, the poorer performance in the sequential condition in the Blalock and Clegg (2010) study could be due to participants not being able to fully construct a global representation because the stimuli were not presented in a simultaneous manner, and this might be influenced by how the test arrays were presented. In all test arrays, information was presented simultaneously, which could encourage the use of relational encoding, instead of an item focused representation, thus providing an advantage to the simultaneous condition. Taken together, evidence suggests that there should be some configural processing advantage in VSTM and VWM, with VSTM benefiting more than VWM.

To explain the disparity between the results of Jiang et al. (2000), Yamamoto and Shelton (2009) and Blalock and Clegg (2010), it could be that multiple levels of the visual representation are encoded and stored. This idea is aligned with the *hierarchical representation hypothesis*. This hypothesis suggests that people encode and store both relational information as well as individual aspects of items (Brady & Alvarez, 2011; Brady & Tenenbaum, 2013). As shown in the above studies, relational information seems to be an important aspect of VMst organisation. However, it could be that different levels of the representation are constrained by decision making. For example, if a task depends more on individual item processing, then having all items presented at decision will increase decision load significantly, harming performance, which could be the case for imagination. A post-cue restricts decision making at test by highlighting a single item to consider in decision and thus exempting all other items on display. If a post-cue is not used, then retrieval and comparison processes are needed to compare each item between the sample and test array which increases decisional load (Palmer, 1990; Palmer et al., 1993; Palmer & Jonides, 1988). Yang et al. (2015) used a colour change detection task to investigate whether different levels of relational information processing are affected by decision load. In a series of experiments, they demonstrated the importance of a post-cue to reduce decisional load and highlighted that task relevant relational information can aid change detection. Therefore, investigating the decisional element of the task might help disentangle performance in VSTM, VWM and imagination. The test arrays used in Experiments 2, 3 and 4 in this thesis all used a post-cue where all items are displayed and only one item is cued. This may help VMst more than imagery because in imagery there was no initial sensory input within which to create a relational structure. As such, the participant might not be able to use relational representations in imagery, and so imagery performance would be reduced.

The present study used the same methodology as Experiment 2 for imagination and visual memory tasks (VWM, VSTM). In both imagination and VM tasks, participants were asked to build up their visual memory or imagination sequentially, whereas in the VSTM task information was presented simultaneously. After this, participants were presented with a post-cue test array. For the current study, there are three types of test array: all five black blocks (whole display), all five black blocks with one block highlighted white (post-cue display) or a single black block (single cue display). Participants were asked to judge whether all of these blocks (whole display) or the cued block was originally cued or not. On half the trials the test array are the originally cued blocks, and in the other half they differ such that one block is in a different location. In addition, set-size 5 was the only set-size presented in the current study and this was identical to Experiment 4. The reasoning for not using set-size 4, even though it produced the most variability in Experiment 2 is due to the high performance found in the VWM task of Experiment 3.

This study aims to understand if the presence of items at test reduce performance in imagination and VMst. It might be that imagination capacity is lower than that of VMst because presentation of items at test disrupts imagination processes more than VMst. In addition, VMst may benefit from greater configural processing when items are represented in their configuration at test such that performance may be enhanced in these conditions relative to the imagination. Based on previous findings from Experiment 2, performance will be better in the VMst tasks than in the imagination task. Furthermore, performance will be higher in the simultaneous VSTM task than the sequential VWM task given the performance (*d*') results of Experiment 2 and the results found in Blalock and Clegg's study (2010), who demonstrated a clear performance advantage for simultaneous presentation over sequential presentation. It is also expected that there will be an effect of display type on performance. In the simultaneous VSTM task performance will be greater in the post-cue condition than the whole display condition. Specifically, although the global organisation is the same between the two conditions (due to five blocks always being presented at test), a post-cue condition advantage is expected because decision factors only apply to one item, whereas in the whole display condition, decision factors apply for each item. In support of this, a post-cue at test has been found to improve performance as they reduce decision making processes to one item which frees up extra cognitive resources that can be used for other processes (Palmer, 1990; Palmer et al., 1993; Palmer & Jonides, 1988; Yang et al., 2015). In addition, in the simultaneous VSTM task performance will be better in the whole display condition than the single cue condition. Specifically, the whole display condition advantage is expected because the global organisation is presented at test, unlike the single cue condition. Similarly, the sequential VWM task will mirror the hypotheses of the simultaneous VSTM task. For imagination it is unclear how performance will differ across the different types of test array. Crucially, if VMst performance is getting a benefit at test because of the relational information and test items interfere with imagery, then eliminating this for the single cue condition should eliminate any VMst advantage. In other words, performance in imagery, VWM and VSTM should be more similar in the single cue condition.

8.2 Method

8.2.1 Participants

Sample size planning was conducted with one-way a = .05 and was based on the 42 participants from Experiment 2 using the smallest effect size observed previously (set-size 5 - VWM and VSTM *d*'), effect size .24 (Cohen's d), and $r = 0.41$ (paired correlation). A priori power analysis indicated 28 participants in the current study to have a 96% power to detect such an effect. Twenty-eight participants (19 Female) took part in the experiment aged between 19 and 30 years (*M* = 21.6, *SD* = 4.6) and had normal or corrected to normal vision. The study took approximately 140 minutes to complete. Each participant received 14 research credits for taking part as a Psychology student through the Psychology Sona System. Nottingham Trent University's Business, Law and Social Sciences Research Ethics Committee approved the study.

8.2.2 Apparatus and materials

This was the same as Experiment 2.

VVIQ

The same inventory is administered in Experiment 1. In the current study all items produce high internal reliability with Cronbach's α = .93.

VOSI

The same inventory is administered in Experiment 2. From the current study, all 14 factors produce high internal reliability with object imagery Cronbach's α =92 and Spatial imagery Cronbach's α =88.

CDQ-R

The same inventory is administered in Experiment 1. In the current study all factors produce high internal reliability with Cronbach's α > .88.

Strategy questions (imagination)

The same questions are administered in Experiment 2.

Strategy question (VWM).

The same question is administered in Experiment 2.

Mathematical proficiency inventory

The same inventory is administered in Experiment 1. In the current study all items produce high internal reliability with Cronbach's α = .85.

8.2.3 Design and procedure

Overview of procedure

Participants first completed the set of questionnaires as described in Experiment 2. Upon completion, the imagination and VMst tasks were counterbalanced across participants Tasks were counterbalanced using a Balanced Latin Square Design. A repeated measures design was used. Once the imagination or VWM task was complete; questions were administered for each of these tasks which investigated the strategies used to complete the task.

Imagination task

The design and procedure were the same as Experiment 2, with the following exceptions. Only set-size 5 was used. In addition, there were three types of test array: all five black blocks (whole display), all five black blocks with one block highlighted white (post-cue display) or a single black block (single cue display). Participants were asked to judge whether all of these blocks (whole display) or the cued block was originally cued or not (see Figure 8.1: panel A). The practice block contained 12 trials: 4 trials were allocated to each of the conditions (test array: whole display, post-cue or single-cue) and of the 4 trials 2 were allocated to the "same" test array presentation and 2 to the "different" test array presentation. 2 of the 4 trials were presented to the left of the display the other 2 were presented to the right of the display. 3 equally balanced main blocks comprised a total of 108 trials. Each test array therefore comprised 36 trials, 18 "same" trials and 18 "different" trials of which 9 were presented to the left and 9 presented to the right of the display. All trials were randomised.

VWM task

The design and procedure were the same as Experiment 2, with the same alterations as presented in the above design section for imagination. See figure 8.1 (panel B) for sequence of events.

VSTM task

The design and procedure were the same as Experiment 2, with the same alterations as presented in the above design section for imagination. See figure 8.1 (panel C) for sequence of events.

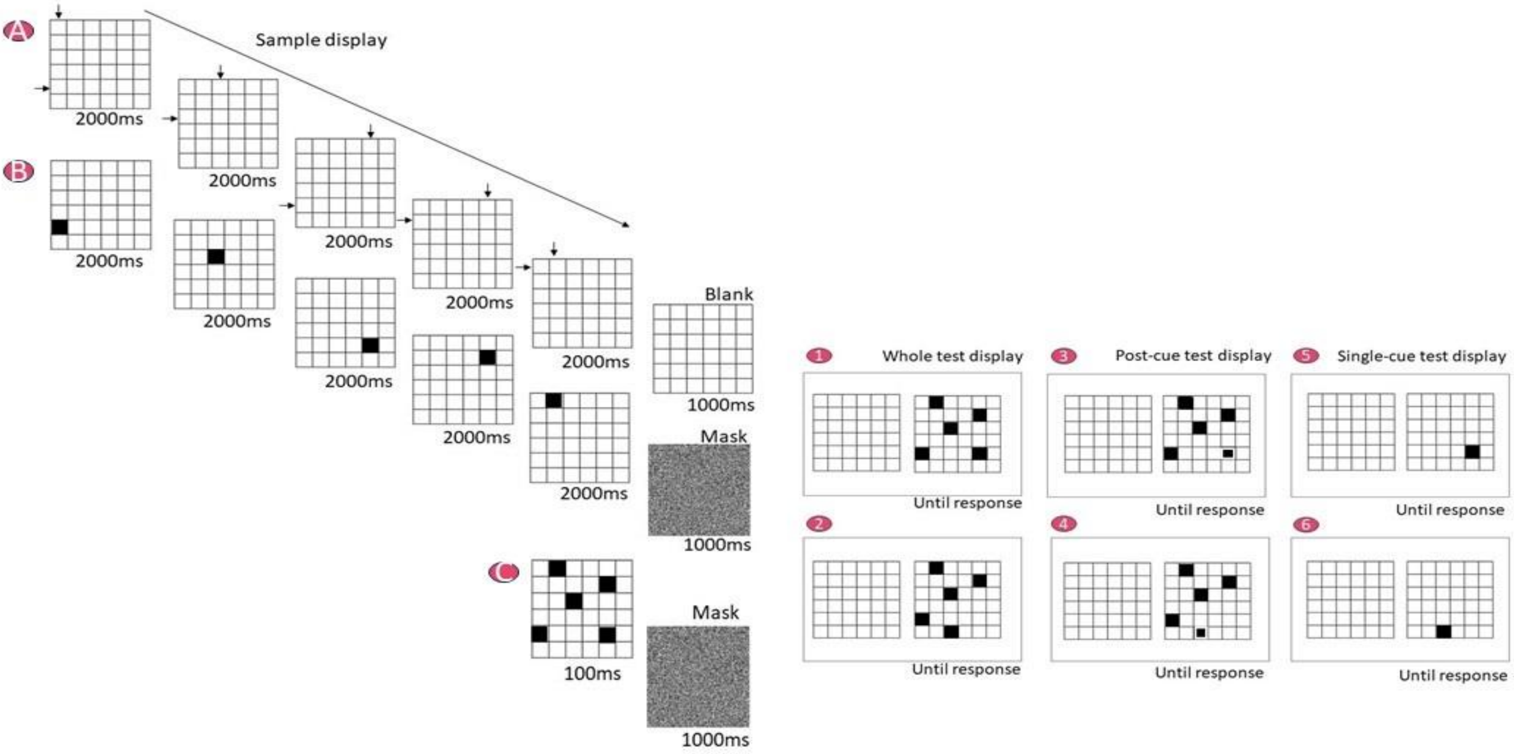

Figure 8.1. Stimuli and sequence of events on visual tasks. Panel A: Imagination task - participants were asked to create a black square in their minds eye at the intersection between the two cue pointers. Panel B: VWM task—Instead of creating a black square in the mind's eye the black square was perceptual presented in a sequential manner. Panel C: VSTM task—all black squares were presented simultaneously. 1 and 2 are whole display change detection tests, 3 and 4 are post-cue change detection tests and 5 and 6 are single-cue change detection tests. 1, 3 and 5) same trial 2, 4 and 6) change trial. An error in 2, 4 and 6 indicates participants could not successfully imagine / remember all five locations accurately.

8.3 Results

8.3.1 Data preparation

The data preparation was the same as Experiment 2. The main analysis included all participant data. Two participants reported using alternative cognitive-strategies (e.g., ‘I gave each black block a specific number to encode its location’). Statistical analysis was re-conducted with these participants removed. Since no evidence of a difference was found, only the main analysis is reported.

8.3.2 Statistical analysis

A 3 (task: imagination, VWM, VSTM) x 3 (test array: whole display, post-cue and single-cue) repeated measures analysis of variance (ANOVA) was carried out on performance (*d*’) and vividness ratings in two separate ANOVAs.

8.3.3 Imagination, VWM and VSTM results

The means and standard deviations for proportion correct for task and test array are shown in Table 8.2. Figure 8.2 clearly shows that performance (*d*’) in the whole and post-cue conditions, was worst for the imagery, slightly better for VWM and better again for VSTM, with the whole and post-cue conditions showing similar levels of *d*’. In the single-cue condition, *d*’ was similar for imagery and VSTM, and better in VWM. A 3 (task: imagination, VWM, VSTM) x 3 (test array: whole display, post-cue, single-cue) repeated-measures ANOVA yielded an effect of task, $F(2, 27) = 22.06$, $p < .001$, $\eta_g^2 = .24$. Post hoc analysis found that VWM performance was significantly better than imagination performance *(p* < .001, *d* = .88), VSTM performance was significantly better than imagination performance (*p* < .001, *d* = .1.03), and there was no significant difference between VWM and VSTM performance (*p* = .355, *d* = .30). There was no effect of test array, $F(2, 27) = 1.03$, $p = .365$, $\eta_g^2 = .01$, but there was a significant interaction effect between task and test array, $F(4, 27) = 8.76$, $p < .001$, $\eta_g^2 = .12$. Post hoc analysis for the imagination task found no significant pairwise differences between any of the test array conditions (all *p* > .093). For the VWM task, single-cue test array produced better performance than whole test array (*p* = .021, *d* = .55), single-cue test array produced better performance than post-cue test array (*p* = .030, *d* = .52), and no significant differences were found between whole test array and post-cue test array (*p* = .954, *d* = .19). For the VSTM task, whole test array produced better performance than single-cue test array (*p* = .002, *d* = .66), post-cue test array produced better performance than single-cue test array (*p* = .001, *d* = .78), and no significant differences were found between whole test array and post-cue test array (*p* = .999, *d* = .04). All post hoc analysis comparing task performance in the different test array conditions across task were significant (*p* < .024), apart from the single-cue condition between imagery and VSTM (*p* = .426, *d* = .29).

Table 8.1. Mean and standard deviations (parenthesis) for proportion correct for task (imagination, VWM, VSTM) across test array (whole, post-cue, single-cue).

	Imagination			VWM			VSTM		
Test array	Whole	Post-cue	Single-cue	Whole	Post-cue	Single-cue	Whole	Post-cue	Single-cue
Proportion correct	.64 (.08)	.66 (09)	.68 (.12)	.72 (.12)	.74 (13)	.80 (.13)	.79 (.15)	.80 (.13)	.72 (11)

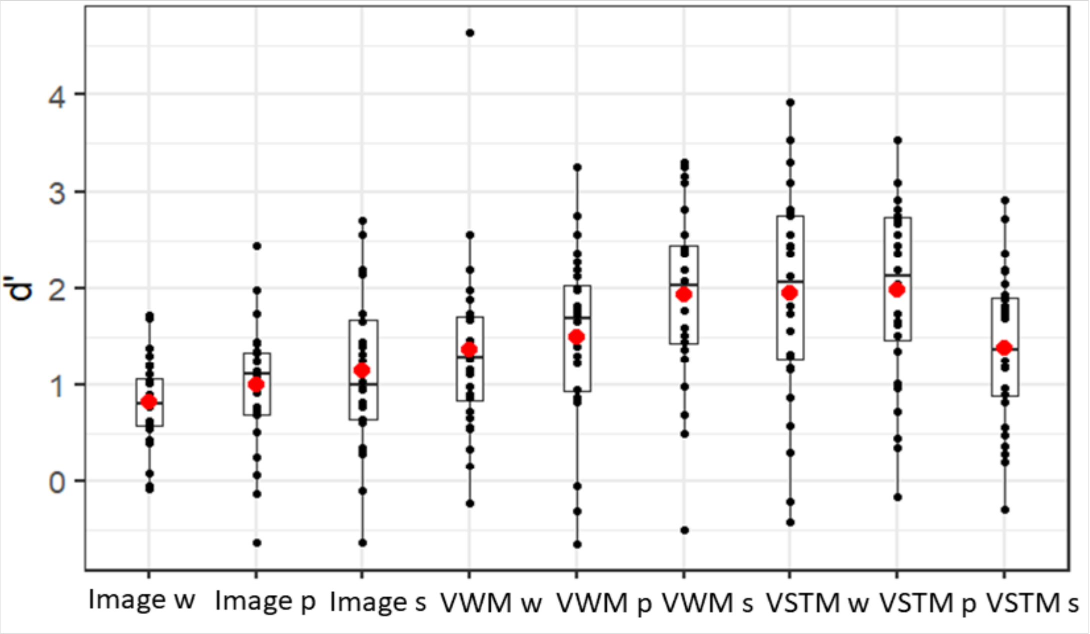

Figure 8.1. *d'* for each task (imagination (image), VWM and VSTM) with each test array presentation (whole display (w), post-cue (p) and single-cue(s)).

In Figure 8.3, mean imagery vividness scores can be seen for test array on imagery, VWM and VSTM. There is a reduction in vividness for imagery in comparison to VWM and VSTM. However, only VSTM vividness was influenced by test array, with lower vividness ratings for the single-cue than either the whole display or post-cue. A 3 (Task: imagination, VWM, VSTM) x 3 (test array: whole, post-cue, single-cue) repeated measures ANOVA was conducted on mean imagery vividness. There was a main effect of task, *F*(2, 27) = 25.99, *p* < .001, $\eta_g^2 =$ .38. Post hoc analysis found that VWM vividness ratings were significantly more vivid than imagination vividness ratings (*p* < .001, *d* = 1.18), VSTM vividness ratings were significantly better than imagination vividness ratings (*p* < .001, *d* = 1.10), and there was no significant difference between VSTM and VWM vividness ratings (*p* = .820, *d* = .21). There was a significant effect of test array, *F*(2, 27) = 14.69, *p* < .001, $\eta_g^2 =$ .09. Post hoc analysis demonstrated that whole test array vividness ratings were significantly better than post-cue vividness ratings (*p*= .028, *d* = .53), whole test array vividness ratings were significantly better than single-cue vividness ratings (*p* < .001, *d* = .85) and post-cue test array vividness ratings were significantly better than single-cue vividness ratings (*p* = .003, *d* = .61). There was a significant interaction effect between task and test array, *F*(4, 27) = 13.28, *p* < .001, $\eta_g^2 =$ .09. Post hoc analysis found no significant differences for imagination between any of the conditions (*p* > .170). Similarly, for the VWM task, no significant differences were found for vividness scores between any of the conditions (*p* > .594). For the VSTM task, whole test array produced better vividness ratings than single-cue test array (*p* < .001, *d* = .1.04), post-cue test array produced better vividness ratings than single-cue test array (*p* < .001, *d* = .95), and no significant differences were found between whole test array and post-cue test array (*p* = .395, *d* = .29). All post hoc analysis comparing task vividness in the different test array conditions across task were significant (*p* < .050), apart from the post-cue condition between VWM and VSTM (*p* = .091, *d* = . 43).

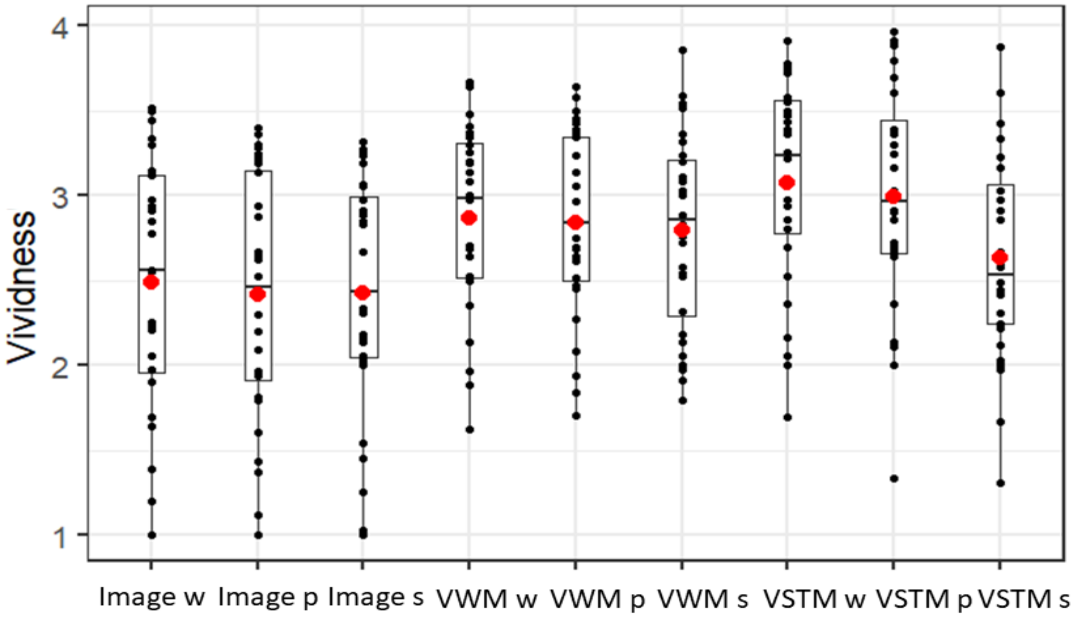

Figure 8.3. Vividness for each task (imagery (image), VWM and VSTM) with each test array presentation (whole display (w), post-cue (p) and single-cue (s)).

8.3.4 Correlations

The means and standard deviations for questionnaire measures and strategy inventory are reported in Table 8.2. Correlations were computed on the data of 28 participants. Table 8.3 shows correlations between imagination, VWM and VSTM performance in each of the test array conditions (whole display, post-cue and single-cue) with questionnaires. Table 8.4 presents correlations between imagination *d*' (whole display, post-cue and single-cue) and strategy inventory questions. There were several findings of note.

A positive relationship was found between VWM and VSTM across conditions (whole display, post-cue, single cue). In contrast, imagination and VMst correlations depended upon the type of test array. Imagination whole display did not correlate with any of the VMst conditions, whereas imagination post-cue condition positively correlated with VWM post-cue and VWM / VSTM single cue. In addition, a positive relationship was found between imagination single cue and VWM / VSTM single cue. Previous experiments in this thesis found that imagination and VWM were more strongly correlated than VWM and VSTM.

The single-cue condition of the imagination task positively correlated with the VVIQ questionnaire (see Table 8.3). However, note that a numerical positive correlation is a conceptual negative correlation here. Furthermore, the imagination single-cue condition negatively correlated with the VOSI and the CDQ-R questionnaire (see Table 8.3). No other imagination or VMst conditions correlated with any of the questionnaire measures. No other experiment in this thesis has found a significant relationship between the VVIQ / VOSI and imagination, as such it is not clear why this relationship exists.

Table 8.2. Descriptive results of imagination strategy questions, VVIQ, VOSI and subscales CDQ-R and subscales and mathematical proficiency.

	M	*SD*
After the cues were presented, I used them as I was asked to	4.11	0.69
I often did not imagine the objects	3.21	1.20
When tested I remembered the cues instead of thinking about the imagined objects	3.14	1.01
I used words and/or sentences to help myself remember	4.11	1.10
I used numbers to help myself remember	2.96	1.53
After the cues I vividly imagined the object, as if I could see it in front of me	3.39	1.13
The arrows made it possible for me to know which cell I were to imagine the object in	3.86	1.01
VVIQ	39.86	12.13
VOSI (object vividness)	44.82	10.85
VOSI (spatial vividness)	34.75	9.88
VOSI (total)	79.57	19.48
CDQ-R (interaction)	16.21	5.27
CDQ-R (drama)	12.46	4.99
CDQ-R (maths and science)	12.07	4.05
CDQR (arts)	8.50	3.56
CDQ-R (total)	49.25	13.65
Mathematical proficiency	10.50	2.43

Note. *N* = 28.

Table 8.3. Correlations among imagery, VWM and VSTM performance (*d*’) (whole display, post-cue and single-cue) and questionnaires: VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Imagery whole (*d*')	-																		
2	Imagery post-cue (*d*')	.18	-																	
3	Imagery single-cue (*d*')	**.43***	.23	-																
4	VWM whole (*d*')	.10	.33	.31	-															
5	VWM post-cue (*d*')	.22	**.49****	**.42***	**.69****	-														
6	VWM single-cue (*d*')	-.03	**.47***	.32	**.38***	**.58****	-													
7	VSTM whole (*d*')	.12	.34	**.48***	**.43***	**.64****	**.60****	-												
8	VSTM post-cue (*d*')	-.05	.27	.30	**.46***	**.58****	**.62****	**.69****	-											
9	VSTM single-cue (*d*')	.02	**.47***	**.44***	.33	**.53****	**.70****	**.63****	**.60****	-										
10	VVIQ	.17	-.21	**.46***	.23	.30	.12	.30	.01	-.01	-									
11	VOSI (object vividness)	-.06	.12	-.37	-.20	-.21	-.27	-.32	-.01	-.11	**-.84****	-								
12	VOSI (Spatial vividness)	-.12	.17	**-.49****	.07	-.05	-.12	-.36	-.04	-.17	**-.67****	**.77****	-							
13	VOSI (total)	-.09	.15	**-.46***	-.08	-.14	-.21	-.36	-.02	-.15	**-.81****	**.95****	**.93****	-						
14	CDQ-R (interaction)	-.10	-.09	**-.51****	-.21	-.15	-.13	-.27	-.14	-.29	**-.42***	**.51****	**.53****	**.55****	-					
15	CDQ-R (drama)	.28	.14	**-.44***	-.16	-.18	-.22	-.19	-.20	-.29	**-.48***	**.58****	**.60****	**.62****	**.65****	-				
16	CDQ-R (maths and scienc	.01	-.01	-.25	.25	.06	.06	-.02	.17	-.08	-.24	.34	.36	.37	**.57****	.27	-			
17	CDQR (arts)	-.18	.11	-.17	.11	.12	.16	.22	.28	.16	-.24	.31	.14	.25	**.38***	**.40***	.22	-		
18	CDQ-R (total)	-.18	.04	**-.48***	-.04	-.07	-.07	-.12	-.01	-.20	**-.47***	**.59****	**.57****	**.62****	**.89****	**.80****	**.67****	**.62****	-	
19	Mathematical proficiency	-.07	-.03	-.26	.19	.00	-.04	-.16	.20	-.11	-.34	**.47***	**.41***	**.47***	.26	.20	**.62****	.25	**.42***	-

Note. *N* = 32, two-tailed test; *p<.05, **p<.01.

Table 8.4. Correlations among imagination *d*’ (whole display, post-cue and single cue) and task strategy questions.

		1	2	3	4	5	6	7	8	9	10
1	Imagination whole display (d')	-									
2	Imagination post-cue (d')	.18	-								
3	Imagination single-cue (d')	**.43***	.23	-							
4	After the cues were presented, I used them as I was asked to	-.07	-.09	-.35	-						
5	I often did not imagine the objects	-.10	-.06	-.11	-.29	-					
6	When tested I remembered the cues instead of thinking about the imagined objects	-.25	.12	.08	-.14	**.59****	-				
7	I used words and/or sentences to help myself remember	.18	.04	.16	.39*	-.18	-.04	-			
8	I used numbers to help myself remember	.28	-.06	.23	-.08	.15	.24	.19	-		
9	After the cues I vividly imagined the object, as if I could see it in front of me	-.07	.14	-.34	.37	**-.62****	-.37	.13	-.12	-	
10	Did the arrows make it possible for you to know which cell you were to imagine the object in?	.13	-.30	-.18	.40*	-.15	-.28	.20	.00	.21	-

Note. *N* = 32, two-tailed test; *p<.05, **p<.01.

8.4 Discussion

The study was designed to investigate how different test arrays (post-cue, whole display and single-cue) influence performance in imagery, VWM and VSTM. It was suggested that imagination capacity may be lower than VMst as VMst may benefit from the presentation of the visual stimuli during the sample array. This could enable greater relational processing for VWM and VSTM than imagination as items are represented in their configuration at test. Additionally, imagination processes may be disrupted by the presentation of items at test more than VMst because the black blocks at test were not seen during imagination generation, whereas they were seen during encoding for VWM and VSTM. Presenting all the stimuli at test could therefore benefit VMst in comparison to imagination due to two reasons; 1) because the actual presentation of these stimuli during initial presentation may allow for relational memory to play a role, and 2) imagination processes may be disrupted by presenting all the stimuli at test. As such better VMst performance in Experiment 2 may be due to the method of test (all stimuli are shown, and one is post-cued). This experiment therefore manipulated the test display, either using a post-cue (all items presented with a single item cued), a whole display condition (a judgement is made about whether the whole display is the same or not), or a single cue condition (only one item is presented), if relational processing is important then VSTM and VWM should show worse performance in the single cue condition. Furthermore, the single cue condition should reduce any interference for imagination.

The present study demonstrated that imagery performance (*d*') and vividness was lower than that of VWM and VSTM with VWM and VSTM producing similar performance and vividness. This pattern is similar to that seen in Experiment 2. Critically, the type of test array used influenced performance in each of the tasks differently. For VWM performance was better in the single cue condition, with comparable performance in the other two types of test display. In contrast, for VSTM performance was considerably poorer in the single-cue condition than the other two test displays which had comparable levels of performance. Unlike both VWM and VSTM, test display had no impact on imagery performance. This suggests that configural information and decision factors influence imagery, VSTM and VWM differently.

Relational processing

The test array findings for VSTM, VWM and imagination suggest that these tasks are not underpinned by identical processes. VSTM performance was better in the whole display and post-cue conditions than in the single cue condition, these findings support the relational information hypothesis (Alvarez, 2011) and the findings of Jiang et al. (2000) that VSTM is supported by global spatial relations. VSTM is therefore hindered by the presentation of a single item at test. Interestingly, when relational information at decision was removed then VSTM performance becomes similar to imagery performance in the single cue condition. This supports the idea that relational information was supporting VSTM performance in Experiment 2. In contrast, VWM might be underpinned by a system that independently codes each item (Woodman et al., 2012) and so other display objects provide a distraction and complicate the decision process, leading to worse performance. Many models of VWM include the notion of a focus of attention (Cowan, 2001; Cowan et al., 2020; Oberauer & Hein, 2012). The sequential stimulus build up in a VWM task therefore enables this focus of attention to be directed at each individual item (Yamamoto & Shelton, 2009). Therefore, this single focus of attention may be best suited to single report procedures.

Alternatively, the impact of test array may be due to the way in which the test array matched the encoding presentation. For example, in the VWM task participants were asked to sequentially build-up an image item by item and an advantage was shown for the single-cue test array. Whereas in the VSTM task participants were shown the stimuli simultaneously and an advantage was shown when all items were presented at test (whole display and post-cue). Therefore, each of these tasks benefited when the test array matched the way in which participants encoded the items. However, Lecerf and de Ribaupierre (2005) found a simultaneous presentation advantage for both whole display and single-cue test arrays which suggests that the test array presentation does not have a large effect on encoding. Furthermore, participants in the imagery task were asked to build-up an image sequentially, similar to that of the VWM task but test display did not influence performance in the imagination task. This provides some evidence against an explanation based on better performance when the test display presentation matches the format of the initial stimulus presentation.

Crucially, unlike the other tasks, imagery was not affected by the test display manipulation. This suggests that presenting items at test did not interfere with the content of the imagined representations or increase decisional noise. Furthermore, the lack of effect of test array on imagination performance suggests that there was no configural benefit or any clear evidence for a predominance of independent item coding. It may be that this could be tentatively explained by the hierarchical representation hypothesis which posits that both featural and relational information are encoded and stored (Brady & Alvarez, 2011; Brady & Tenenbaum, 2013). It could be that the process of generating the stimulus and maintaining the configuration meant a much weaker configural representation in imagination than in VWM. However, it is difficult to solidly conclude on these issues.

Taken together the current findings suggest that the decisional component is not responsible for the performance differences between imagination and VWM in Experiment 2. However, performance was more similar in the single cue condition for imagination and VSTM which strongly suggests that VSTM performance is boosted by representing the relational information at test and could help explain the capacity differences found between imagination and VSTM in Experiment 2. Additionally, imagery performance did not change across decisional conditions, it is therefore unclear whether imagery benefitted from relational encoding or not.

Explanation of the poor imagery performance

The poorer performance of imagery in comparison to VMst corroborate with the findings from Experiment 2, and Experiment 3 and 4 (imagery and VWM only) and could be due to the absence of bottom-up sensory input, the use of separate systems and the reliance on top-down processes during imagery as previously stated in the general discussion section of Experiment 2 (see section 5.5.4). In addition, imagery vividness was reduced in comparison to VMst across all conditions. These findings further support the findings from Experiment 2, and Experiment 3 and 4 (imagery and VWM only) and broadly mirror the performance differences. As such, the vividness findings could reflect the explanations given for the performance differences.

Chapter 9: Experiment 6

This experiment was preregistered with the Open Science Framework: OSF Registries | The capacity of visual imagery, visual working memory and visual short-term memory for features

9.1 Introduction

Experiment 2 investigated the capacity limitations of imagination and VMst. The capacity of imagination was severely capacity limited and lower than that found in visual memory. However, little is known about how many features (e.g., colour and location) can be maintained within imagination, and whether the capacity is the same or different to known capacities in VMst. Unlike in Experiment 2, which explored item location only, the current study measures the ability of participants to bind different colour to a particular location in visual memory and imagination.

In VSTM tasks (e.g., Luck & Vogel, 1997) binding colour to a particular location is standard in determining VSTM capacity. In a series of experiments Luck and Vogel (1997) manipulated the number of objects as well as features (e.g., colour, orientation) and conjunctions (e.g., dual-colour stimuli), and found that capacity is defined by the number of objects rather than features. More recent evidence has also found that capacity is set by objects rather than features (Luria & Vogel, 2011). In contrast, other researchers define features as having their own independent stores with the limit depending upon how many features are from the same dimension (Shin & Ma, 2017; Wang et al., 2017; Wheeler & Treisman, 2002). For example, objects that have multiple dimensions of a feature (e.g., 6 objects with 6 discernible colours) are remembered less well than objects that have a single dimension of a feature (e.g., 6 objects that are all the same colour). Using the classic change detection paradigm (for details see section 2.2.3) Wheeler and Treisman (2002) found evidence for separable feature stores that have their own capacity. Moreover, it was found change detection for bound features (e.g., colour and location) was worse than non-bound features (e.g., location only). These findings suggest that independent feature stores have their own capacity limit and that feature binding (e.g., colour and location) has an additional limitation, independent of the feature stores. More recent evidence has found similar binding limitations in both whole display and single-cue change detection designs (Brown & Brockmole, 2010; Ueno et al., 2011).

Crucially, Wheeler and Treisman (2002) state that focused attention is important for feature bindings, and there is evidence to suggest that changing location can disrupt memory bindings

(Treisman & Zhang, 2006). Indeed, much research supports the idea that attention plays a crucial role when location is task relevant (Awh & Jonides, 2001; Treisman & Zhang, 2006; Woodman & Luck, 2004; Fougnie & Marois, 2006). However, the brain can only attend to a small subset of simultaneously presented stimuli, and in turn, this causes less brain activation and even suppression of the other stimuli (Kastner et al., 1998; Kastner et al., 2001). Therefore, if numerous objects require binding, and if attention is crucial for binding process, then there will be a limited ability to successfully attend to multiple areas simultaneously.

In terms of VWM it has also been shown that increasing the number of features of objects decreases VWM performance. Oberauer and Eichenberger (2013) used changed detection to investigate the effect of individual features and conjunctions of features on VWM capacity. They found a decrease in change detection performance when integrating multiple features within an object compared to single feature objects. The largest decrease in performance was found when increasing features from 1 to 3 features with a smaller decrease in performance found between 3 to 6 features. These results are comparable to those found in the VSTM literature (e.g., Wheeler & Treisman, 2002). Taken together, this evidence suggests that both VSTM and VWM capacity will be reduced when increasing complexity of objects.

Given VWM capacity appears to be impacted by featural complexity, then if imagination relies on the same systems (and is the same process) then the same effect should be found in imagination. However, it could be that imagination capacity is further reduced in comparison to simpler imagined objects (e.g., only imagining black blocks) by increasing the number of features. Visual imagery has been associated with stronger top-down activations than images that are externally perceived (Dijkstra et al., 2017) and these top-down connections are associated with selective attention during encoding, executive processing and general attentional control (Ishai et al., 2000; Mayer et al., 2007; Zanto et al., 2011). Previous findings from Experiment 2 suggest that visual imagery requires top-down processing in order to generate an image. It has been suggested by others that there might be a role of the central executive in imagery (Logie, 1995, 2003; Rudkin et al., 2007). Recently Hitch et al. (2020) suggests that the maintenance of bindings may require a refreshing process via the Central Executive. If this is the case, then the refreshing process of binding colour to location should place extra load onto the central executive, which is already involved in generating a mental image. This could further reduce visual imagery performance and capacity. However, it may well be that the generation of an object is no more difficult than when the objects are of increased complexity and the maintenance component of imagery is the same as that used by memory.

The present study used the same methodology as Experiment 2 for imagination and visual memory tasks (VWM, VSTM). However, unlike Experiment 2, which required participants to imagine/remember black blocks, participants are required to bind colour to a particular location. In both imagination and VWM tasks, participants are asked to build up their imagination or memory sequentially. In the VWM task, coloured blocks are placed in a particular location in a grid. Whereas, in the imagination task, information is presented on the outer edge of the grid via a letter on the column and an arrow on the row. At the intersection of the cues, participants are to imagine a coloured block. The letter indicates the colour of the block to-be-imagined (e.g., R represents a red block to-be-imagined) and the arrow, along with the letter, identifies the position of the to-be-imagined block. Finally, in the VSTM task, coloured blocks are presented simultaneously in particular positions in a grid. In all tasks, at test participants are presented with a single-cue and asked whether the cued object was the right colour at that location. In half the trials the single-cue is the originally cued block and in the other half it differs such that colour is randomly selected from one of the other colours previously presented in the trial. Set-size was manipulated (3, 4, 5, and 6) in order to derive capacity estimates from each of the tasks.

The study aims to understand the impact of object complexity on imagination, and whether the capacity is the same or different to that of visual memory in the short-term. In line with prior research (e.g., Oberauer & Eichenberger, 2013), it was expected that increasing object complexity would reduce VWM capacity relative to Experiment 2. In terms of imagery, it is unclear how increasing object complexity will impact performance. It may be that generation of an object is no more difficult when the objects are of increased complexity. If so, and the maintenance of that image uses the same processes as the maintenance of a memory, then the increase of the complexity of the objects should harm performance in the imagery task to the same extent as performance in the VWM task in Experiment 2. However, if generation of more complex objects is more effortful then there may be an overall additional impact on the performance of the imagery task relative to the VWM task. For the VSTM task, it is important to consider that in Experiment 2 the simultaneous presentation of stimuli may have facilitated use of global configuration. However, increasing object complexity means binding feature information, which may be attentionally demanding (Baddeley, 2000; Wheeler & Treisman, 2002). As such, this may mean the global configuration is less useful, reducing VSTM performance relative to Experiment 2. Furthermore, sequential versus simultaneous presentation might impact performance in this binding task. It has been shown that sequentially presenting stimuli versus simultaneously presenting stimuli improves performance in colour change detection tasks (Emrich & Ferber, 2012; Fougnie & Marois, 2009; Ihssen et al., 2010; however other studies have found the opposite to be true, see section 2.2.4). This is thought to be due to factors such as, increasing distinctiveness of stimuli by focusing attention at a specific location in sequential displays (Yamamoto & Shelton, 2009), less item confusion (Frick, 1985) and less competition between stimuli (Desimone & Duncan, 1995; Kastner et al., 1998; Kastner et al., 2001). Recent evidence has also shown that sequentially presenting information allows for integration of individual features during the maintenance period (Galeano et al, 2020). In contrast, during the VSTM task, multiple objects need to be encoded simultaneously which potentially requires the allocation of attention to numerous objects and could reduce the binding of information. Together this suggests that, in a binding task performance might be better for sequential presentation. If so, it is expected that equivalent performance may be found between the imagination and VSTM tasks, whereas performance will be better in the VWM task than in the VSTM task.

9.2 Method

9.2.1 Participants

Sample size planning was conducted using .05 (one way) significance level and was based on the 42 participants from Experiment 2 using the smallest effect size observed previously (set-size 5 - VWM and VSTM *d*'), effect size .24 (Cohen's d), and $r = 0.41$ (paired correlation). A priori power analysis indicated 27 participants in the current study to have a 98% power to detect such an effect. Twenty-seven participants (17 Female) took part in the experiment aged between 18 and 39 years ($M = 27.19$, $SD = 5.72$) and had normal or corrected to normal vision. The study took approximately 150 minutes to complete. Each participant received 15 research credits for taking part as a Psychology student through the Psychology Sona System. Nottingham Trent University's College Research Ethics Committee approved the study.

9.2.2 Apparatus and materials

This was the same as Experiment 2.

VVIQ

The same inventory is administered in Experiment 1. In the current study all factors produce high internal reliability with $\alpha = .82$ Cronbach's.

VOSI

The same inventory is administered in Experiment 2. From the current study, all 14 factors produce high internal reliability with object imagery Cronbach's $\alpha = .90$ and spatial imagery Cronbach's $\alpha = .86$

CDQ-R

The same inventory is administered in Experiment 1. In the current study all factors produce high internal reliability with Cronbach's $\alpha > .85$.

Strategy questions (imagination)

The same questions are administered in Experiment 2.

Strategy question (VWM)

The same question is administered in Experiment 2.

Mathematical proficiency inventory

The same inventory is administered in Experiment 1. In the current study all items produce high internal reliability with Cronbach's $\alpha = .83$.

9.2.3 Design and procedure

Overview of procedure

Participants first completed the set of questionnaires as described in Experiment 2. Upon completion, the imagination, VWM task, VSTM task, forward Corsi block task and backward Corsi block task were counterbalanced across participants using a Balanced Latin Square Design. A repeated measures design was used. Once the imagination task or VWM task was complete; questions were administered for each of these tasks which investigated the strategies used to complete the task.

VWM task

The design and procedure were the same as Experiment 2 with the following exceptions. Participants had to remember a set of coloured blocks which were sequentially presented every two seconds within a grid (Figure 9.1: panel B). The number of blocks (set-size) was manipulated (3, 4, 5 and 6). There were 6 possible colours: red (1, -1, -1), green (-1, 1, -1), blue (-1, -1, 1), yellow (-1, 1, 1), purple (0.5, 0, 0.5) and cyan (0, 1, 1). Repetition of colour was allowed. However, within a trial, the same colour could not be repeated more than twice and only one colour could be repeated (the reason for this is discussed below in the design and procedure of the imagination task). At test, only a single-cue was presented in the test array. This did not allow participants to strategically count which colours were presented in the test array. The only way to eliminate a counting strategy was to present a single-cue at test. Participants were asked to judge whether this block was originally viewed or not. On half the trials the test display was the originally cued block ("same" trial), and in the other half differed such that the colour of the presented block was randomly selected from other colours previously cued ("different" trials).

The practice block contained 8 trials: two trials were allocated to each of the set-size conditions (3, 4, 5. 6) and of the two trials, one trial was allocated to the "same" test array presentation and two to the "different" test array presentation. Half of the trials were presented from the left of the display and the other half was presented from the right of the display, equally balanced between the "same" and "different" test array presentations.

Participants then completed 144 trials across 3 equally balanced main blocks. Within each block, each set-size (3, 4, 5, 6) was presented 12 times, there were 6 same trials and 6 different trials, all presented in a random order. Participants were able to take a short break after completing each block.

Imagination task

The design and procedure were the same as Experiment 2, with the same alterations as presented in the above design section for VWM with the following exceptions. The to-be imagined coloured blocks were cued with a black (-.2, -.2, -.2) letter on the column and a black (-.2, -.2, -.2) arrow on the row of the grid indicating participants to imagine a coloured block at the intersection of these cues. The colour to be imagined was set by the letter presented on the column (R = red, G = green, B = blue, Y = yellow, P = purple and C = cyan). The cues designate a location and colour to be imagined (Figure 9.1: panel A). Repetition of one colour per trial was allowed because there is only a limited amount of highly discernible colours that can be selected and allocated to specific letters. For example, B = blue, therefore B for black could not be used as one of the cued colours. In addition, some letter cues are similar in structure. For example, O could represent the colour orange, however the structure of the letter O is similar to that of G and so participants could imagine the wrong colour due to the similarities in letter structure. Therefore, it was deemed acceptable to use repetition of colours.

VSTM task

The design and procedure were the same as Experiment 2, with the same alterations as presented in the above design section for VWM with the following exception. Coloured blocks were presented simultaneously during the sample array for 100ms (Figure 9.1: panel C).

Forward Corsi block task

This is the same task that was administered in Experiment 1.

Backwards Corsi block task

This is the same task that was administered in Experiment 2.

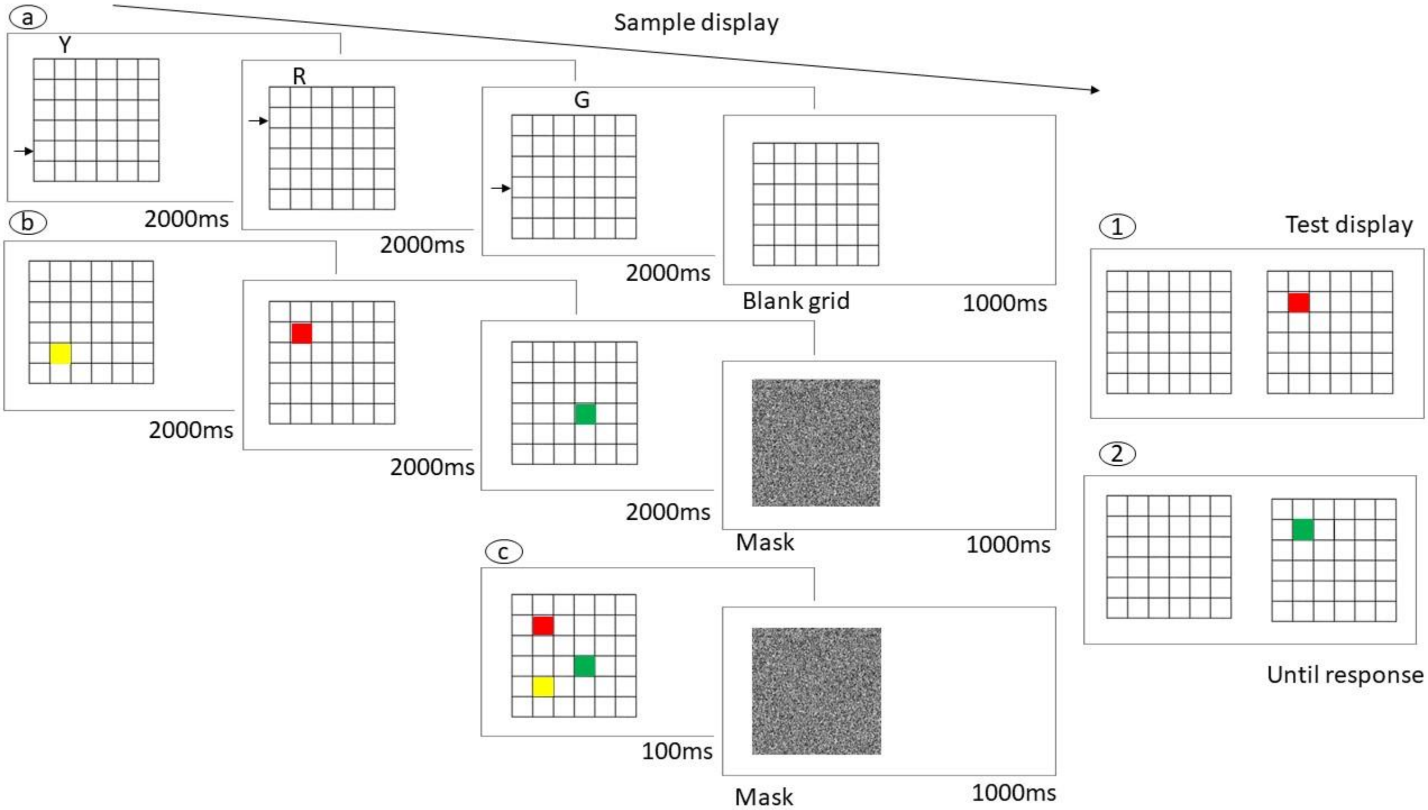

Figure 9.1. Stimuli and sequence of events in visual tasks with set-size 3 items. Panel A: Imagination task -participants were asked to create coloured blocks in their minds eye at the intersection between the letter cue and the arrow cue (e.g., at the start of the sequence participants should imagine a yellow block at the intersection of the Y and the arrow). Panel B: VWM task—coloured blocks were visibly presented on screen in a sequential manner. Panel C: VSTM task—all coloured blocks were presented simultaneously. 1) same trial 2) change trial.

9.3 Results

9.3.1 Data preparation

The data preparation was the same as Experiment 1. The main analysis included all participant data. Five participants reported using alternative cognitive strategies (e.g., ‘I used words to remember or imagine the colour of each block’). Statistical analysis was re-conducted with these participants removed. Since no evidence of a difference was found, only the main analysis is reported.

9.3.2 Statistical analysis

The statistical analysis was the same as Experiment 1 with the following exceptions. For the VWM, imagery and VSTM tasks a 3 (task: VWM, imagery, VSTM) x 4 (set-size: 3, 4, 5, 6) repeated measures analysis of variance (ANOVA) was carried out on performance (*d*') and vividness ratings in 2 separate ANOVAs.

9.3.3 Imagination, VWM and VSTM results

The means and standard deviations for proportion correct for set-size are shown in Table 9.1. Figure 9.2 shows *d'* (top) and vividness (bottom) for all tasks as a function of set-size. *d'* and vividness decrease as set-size increases for all tasks. VWM performance is higher than that of imagination and VSTM, and VSTM performance is higher than imagination. A 3 (task: Imagination, VWM, VSTM) x 4 (set-size: 3, 4, 5, 6) repeated-measures ANOVA was conducted on *d*' and yielded an effect of task, *F*(2, 52) = 3.66, *p* = .032, $\eta_g^2 = .06$. Post hoc analysis found that VWM performance was significantly better than imagination performance (*p* = .008, *d* = .64). There was no significant difference between VSTM performance and imagination performance, (*p* = .562, *d* = .26) and no significant differences between VWM and VSTM performance (*p* = .735 *d* = .23). There was an effect of set-size, *F*(3, 78)= 80.11, *p* < .001, $\eta_g^2 = .39$, with a significant linear trend, *F*(1, 26)= 161.83 , *p* < .001 signifying that as set-size increased, performance decreased approximately additively, and no interaction effect, *F* < 1.

Table 9.1. Mean and standard deviations (parenthesis) for proportion correct for task (imagery, VWM and VSTM) across set-size (3, 4, 5 and 6).

	Proportion correct		
Set-size	Imagery	VWM	VSTM
3	.84 (.11)	.87 (.12)	.87 (.10)
4	.77 (.12)	.82 (.13)	.78 (.14)
5	.71 (.10)	.76 (.14)	.75 (.11)
6	.67 (.09)	.73 (.13)	.68 (.09)

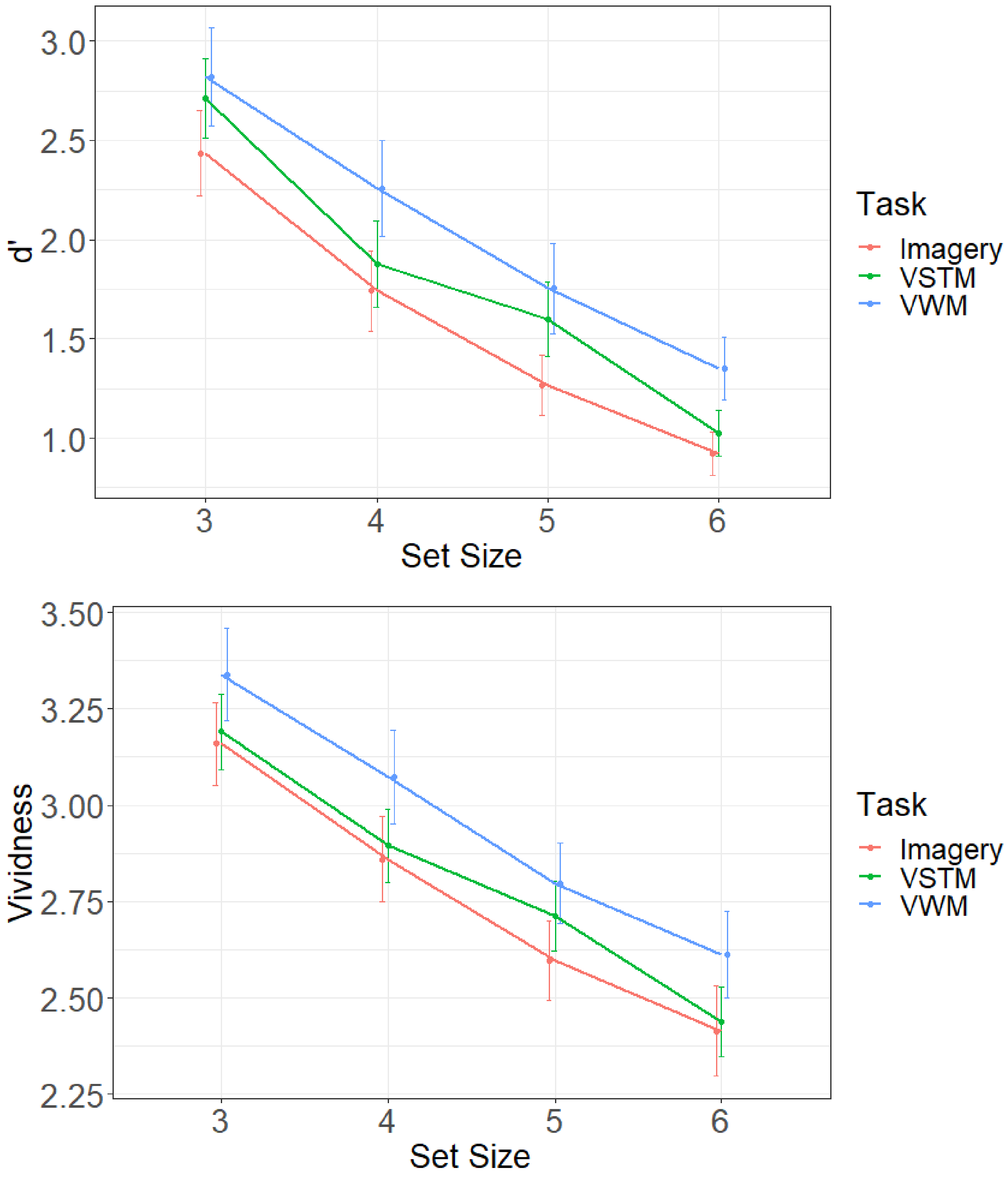

Figure 9.2. *d*' (top) and vividness (bottom) as a function of set-size (3, 4, 5, 6) for the imagery, VWM and VSTM (error bars indicate standard errors).

A 3 (task: imagination, VWM, VSTM) x 4 (set-size: three, four, five, six) repeated-measures ANOVA was conducted on mean vividness scores. There was no effect of task, $F(1.58, 41.18) = 1.51$, $p = .231$, $\eta_g^2 = .04$, an effect of set-size, $F(1.25, 32.41) = 65.34$, $p < .001$, $\eta_g^2 = .31$, with a significant linear trend, $F(1, 26) = 73.50$, $p < .001$ and a significant quadratic trend, $F(1, 26) = 4.57$, $p = .042$, signifying that as set-size increases, vividness scores decrease linearly at first, and then tails off as set-size increases, and no interaction effect, $F < 1$.

9.3.4 Modelling procedure and Capacity Estimates

The same single-cue WoMMBAT model (Working Memory Modelling using Bayesian Analysis Techniques; Morey & Morey, 2011) was used as in experiment 2. An estimate of capacity for VWM, imagination and VSTM was generated using the same parameters, the same modelling procedure and the same two models (participant variance model and participant by task) as experiment 2 (for full details see section 5.5.3.6).

In both models, the MCMC chain sample acceptance rates were in the range deemed to be good (between .60 and .90; Table 9.2) and all plots produced good MCMC chain iterations, kernel density estimates and marginal posterior distribution (Figure 9.3).

The modelling revealed that the participant by task interaction model provided the lowest DIC, indicating that task is important in order to understand differences in *k* (Table 9.2).

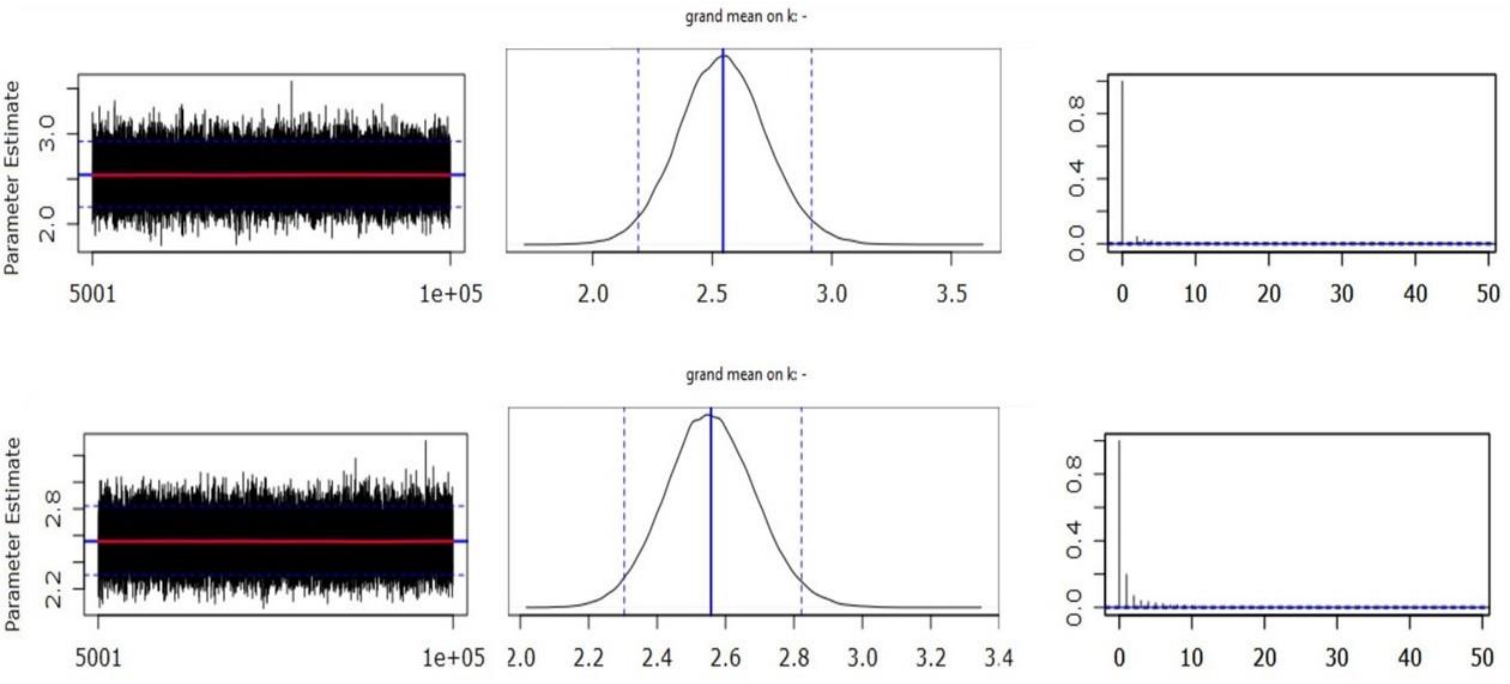

Figure 9.3. Participant variance model (top) and Participant by task model (bottom). MCMC chains: iterations plots (left), Kernel density plots (centre) and autocorrelations plots (right).

Table 9.2. Hierarchical Bayesian model fit statistics for single-cue change detection data for participant variance, interaction (VSTM, VWM and imagination) and each task (VSTM, VWM and imagination).

Model	Number of parameters on *k*	DIC	Acceptance rate	k
Three levels: task type - imagination, VWM, VSTM	81	11187.85	.79	2.56 (overall) 2.31 (imagery) 2.79 (VWM) 2.57 (VSTM)
Participant variance	27	11391.20	.80	2.54 (overall)

Note. *N* = 27. Model ordered from low to high DIC’s.

This model yielded a mean capacity (*k*) of 2.79 items in VWM task, 2.57 items in the VSTM task and 2.31 items in the imagery task. Estimates of *k* for each participant for each task are shown in Figure 9.4. Interestingly, there was significant overlap between the inter-quartile ranges of capacity estimates between the three tasks. A one-way repeated-measures ANOVA was conducted to compare the effect of task (imagination, VWM, VSTM) on *k*. There was a significant effect of task, $F(2, 52) = 3.41$, $p = .041$, $\eta_g^2 = .12$. Post hoc analysis found that VWM *k* was significantly higher than imagination *k* ($p = .006$, $d = .66$), there was no evidence of a difference between VSTM *k* and imagination *k* ($p = .450$, $d = .29$), and no evidence of a difference between VWM and VSTM *k* ($p = .999$, $d = .18$). Re-running the analysis but excluding participants who used a strategy yielded estimates for *k* of 2.86, 2.59 and 2.26 items in VWM, VSTM and imagery respectively.

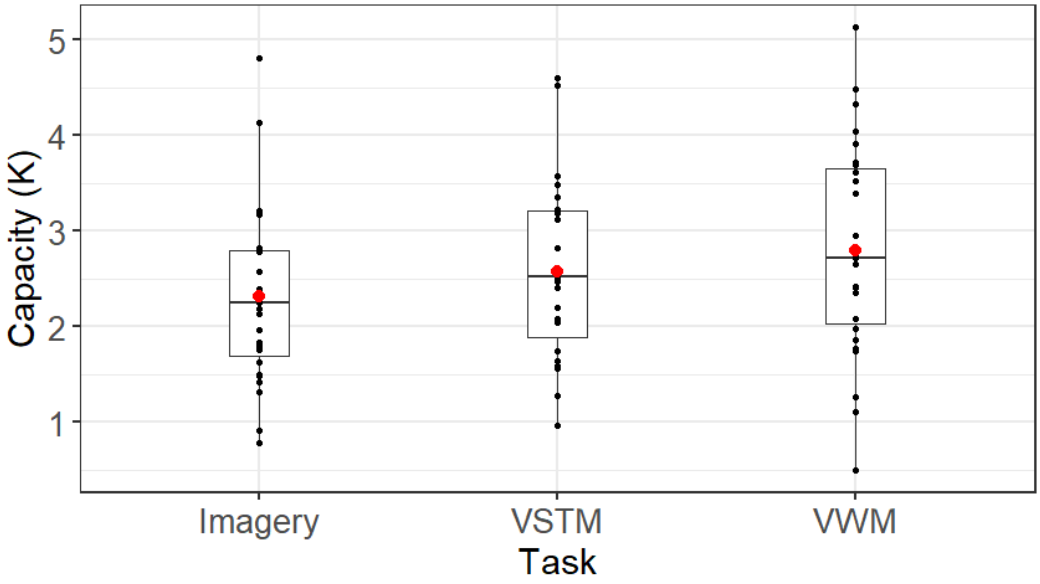

Figure 9.4. Capacity estimates (*k*) for each participant in the imagery, VSTM and VWM tasks. Red dots show mean score.

9.3.5 Correlations

The means and standard deviations for the imagination strategy questions, questionnaire measures and Corsi block forward/backward tasks are reported in Table 9.3. Table 9.4 presents correlations between imagination, VWM and VSTM capacity and performance (*d'*) with questionnaire measures. Table 9.5 shows correlations between imagination, VWM and VSTM capacity and performance (*d'*) with Corsi block forward and backward tasks. Table 9.6 presents correlations between imagination capacity, performance (*d'*) and strategy questions.

Strong positive correlations were found between between imagination and VMst with the strongest correlations found between imagination and VWM (see Table 9.4). This is consistent with imagination and VWM sharing similar processes and corroborates the findings from Experiment 2, 3, 4 and 5. Interestingly, there was no significant correlation found between VWM and VSTM which is surprising given that previous research suggests that VWM and VSTM use a similar short-term maintenance component (for a review see, Aben et al., 2012). In addition, Experiment 2 and Experiment 5 found a strong positive relationship between VWM and VSTM. It is therefore uncertain as to why a strong positive relationship was not found.

Forward Corsi Span positively correlated with VWM capacity whereas the Backwards Corsi Span positively correlated with VSTM capacity. Imagery capacity did not significantly correlate with Forward or Backward Corsi Span (see Table 9.5). These findings show that imagery, VWM and VSTM potentially use separate systems. However, this should be cautiously interpreted given that all three tasks were positively associated with the Forwards and Backwards Corsi Span.

A significant positive relationship was found between VSTM and mathematical proficiency. This finding corroborates with previous research which indicates that VSTM is important for mathematical abilities (Bull et al., 2008; Mix et al., 2016; see Table 9.4).

There was a significant positive relationship between imagination capacity and the strategy question 'after the cues were presented, I used them as I was asked to'(see Table 9.6). Indicating that using the cues correctly during the imagination task benefited capacity. Finally, a significant negative relationship was found between imagination performance (*d*') and the strategy inventory question 'When tested I remembered the cues instead of thinking about the imagined objects' (see Table 9.6). This relationship suggests that remembering the cues instead of imagining the to-be-imagined object reduces performance. Taken together these findings suggest the importance of using the cues to imagine objects.

Table 9.3. Descriptive results of strategy questions (imagination), Corsi block forward task, Corsi block backwards task, VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

	M	*SD*
After the cues were presented, I used them as I was asked to	3.96	0.71
I often did not imagine the objects	2.48	0.89
My ability to imagine the objects were dependent on how many objects were being asked to imagine	4.30	0.61
When tested I remembered the cues instead of thinking about the imagined objects	2.81	1.11
I used words and/or sentences to help myself remember	3.15	1.51
I used numbers to help myself remember	1.70	0.82
After the cues I vividly imagined the object, as if I could see it in front of me	3.22	1.01
Did the arrows make it possible for you to know which cell you were to imagine the object in?	4.19	0.68
Corsi span (forward)	6.44	1.22
Corsi bock total (forward)	64.56	27.16
Corsi span (backwards)	6.26	0.59
Corsi total (backwards)	58.30	12.90
VVIQ	33.22	9.82
VOSI (Object vividness)	51.48	8.33
VOSI (Spatial vividness)	40.48	10.09
VOSI (Vividness Total)	91.96	16.30
CDQ-R interaction	24.74	4.82
CDQ-R Drama	21.37	5.98
CDQ-R maths and science	17.52	4.64
CDQ-R arts	12.15	3.20
CDQ-R Total	75.78	11.99
Mathematical proficiency	10.44	2.69

Table 9.4. Correlations among imagery, VWM and VSTM, performance (*d*') and questionnaires: VVIQ, VOSI and subscales, CDQ-R and subscales and mathematical proficiency.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Imagery *k*	-															
2	VWM *k*	**.77****	-														
3	VSTM *k*	**.49****	.38	-													
4	Imagery *d'*	**.99****	**.72****	**.49***	-												
5	VWM *d'*	**.76****	**.98****	.36	**.71****	-											
6	VSTM *d'*	**.46***	.35	**.99****	**.46***	.34	-										
7	VVIQ	.07	.18	.13	.01	.11	.14	-									
8	VOSI (object vividness)	-.23	-.19	-.13	-.15	-.11	-.15	**-.79****	-								
9	VOSI (spatial vividness)	-.12	-.17	-.17	-.08	-.06	-.19	**-.50****	**.56****	-							
10	VOSI (vividness total)	-.19	-.20	-.17	-.13	-.09	-.19	**-.72****	**.86****	**.91****	-						
11	CDQ-R interaction	-.21	-.23	-.06	-.21	-.19	-.05	-.24	.30	**.40***	**.40***	-					
12	CDQ-R drama	-.20	-.26	-.21	-.18	-.30	-.25	.03	.24	.02	.13	**.43***	-				
13	CDQ-R maths and science	.20	.14	.04	.18	.20	.07	-.04	-.03	.28	.16	.34	-.11	-			
14	CDQ-R arts	.18	-.06	.27	.20	-.12	.26	-.20	.15	-.29	-.10	.16	**.50****	-.17	-		
15	CDQ-R total	-.06	-.18	-.05	-.05	-.18	-.05	-.15	.27	.20	.26	**.79****	**.76****	**.42***	**.52****	-	
16	Mathematical proficiency	.32	.21	**.45***	.27	.21	**.42***	.20	-.24	.25	.03	**.41***	-.02	**.44***	-.02	.32	-

Note. *N* = 27, two-tailed test; *p<.05, **p<.01.

Table 9.5. Correlations among imagination (Imagery), VWM and VSTM, capacity (*k*), performance (*d*') and forward and backwards Corsi span (CS) and forward and backwards Corsi total (CT).

		1	2	3	4	5	6	7	8	9	10
1	Imagery *k*	-									
2	VWM *k*	**.77****	-								
3	VSTM *k*	**.49****	.38	-							
4	Imagery d'	**.99****	**.72****	**.49***	-						
5	VWM *d*'	**.76****	**.98****	.36	**.71****	-					
6	VSTM *d*'	**.46***	.35	**.99****	**.46***	.34	-				
7	Forward (CS)	.36	**.52****	.19	.35	**.55****	.17	-			
8	Forward (CT)	.37	**.48***	.25	.36	**.49****	.24	**.95****	-		
9	Backwards (CS)	.38	.38	**.51****	.37	.34	**.49***	.31	**.41***	-	
10	Backwards (CT)	**.42***	.37	**.49****	**.41***	.36	**.48***	.36	**.47***	**.84****	-

Note. *N* = 27, two-tailed test; *p<.05, **p<.01.

Table 9.6. Correlations among imagination (imagery) capacity (*k*), *d*' (performance) and task strategy questions.

		1	2	3	4	5	6	7	8	9	10
1	Imagery *k*	-									
2	Imagery *d*'	**.99****	-								
3	After the cues were presented, I used them as I was asked to	**.48***	**.51****	-							
4	I often did not imagine the objects	-.25	-.34	-.22	-						
5	My ability to imagine the objects were dependent on how many objects were being asked to imagine	-.15	-.11	-.15	-.20	-					
6	When tested I remembered the cues instead of thinking about the imagined objects	-.36	**-.39***	**-.55****	**-.48***	-.14	-				
7	I used words and/or sentences to help myself remember	.30	.28	**.40***	-.03	-.26	.09	-			
8	I used numbers to help myself remember	-.02	.02	-.09	.05	-.05	.11	.28	-		
9	After the cues I vividly imagined the object, as if I could see it in front of me	.30	.33	**.39***	**-.42***	.08	-.34	**.41***	**.45***	-	
10	Did the arrows make it possible for you to know which cell you were to imagine the object in?	-.03	-.02	**.49****	.04	.14	-.31	.23	-.04	.16	-

Note. *N* = 27, two-tailed test; *p<.05, **p<.01.

9.3.6 Secondary analysis

An unplanned secondary analysis was conducted on the trials in which all colours were different and in which there was a single colour repetition. There were not enough data points in levels of set-size (e.g., 6) no colour repetition (i.e., there were 2502 data points in colour repetition and only 347 data points in no colour repetition) and set-size (3) colour repetition (i.e., there were 2067 data points in no colour repetition and only 802 data points in colour repetition) to calculate average *d*' and proportion correct over set-size (3, 4, 5, 6). It was therefore decided that only set-size 4 would be analysed in each task as this showed approximately equal data points in no colour repetition (1460 trials) and colour repetition (1406 trials) conditions. Any difference here will provide evidence as to whether the number of feature values per se is important in any of the three main tasks.

A 3 (task: imagination, VWM, VSTM) x 2 (repetition: present, absent) repeated-measures ANOVA on *d*' yielded no effect of task, $F(2, 52) = 2.79$, $p = .071$, $\eta_g^2 = .06$, and no effect of repetition, $F < 1$. There was a significant interaction effect between task and repetition, $F(2, 52) = 7.22$, $p = .002$, $\eta_g^2 = .06$. Post hoc analysis found that repetition present affected performance in imagery more than VWM ($p = .003$, $d = .71$). No other results were significant between repetition and task ($p > .064$). Post hoc tests comparing repetition within task found that imagery performance was significantly reduced by colour repetition ($p = .022$, $d = .47$), whereas VSTM performance was significantly reduced by no colour repetition ($p = .009$, $d = .54$). There was no effect of colour on VWM ($p =. 149$, $d = .29$).

A 3 (task: imagination, VWM, VSTM) x 2 (repetition: present, absent) repeated-measures ANOVA on mean vividness scores yielded no effect of task, $F(1.61, 41.96) = 1.41$, $p = .254$, $\eta_g^2 = .05$, an effect of repetition, $F(1, 26) = 10.54$, $p = .003$, $\eta_g^2 = .03$, with vividness scores increasing in the repetition present than repetition absent condition. There was a significant interaction effect between task and repetition, $F(2, 52) = 7.13$, $p = .002$, $\eta_g^2 = .01$. Post hoc analysis found that colour repetition vividness decreased in imagery more than VWM ($p = .041$, $d = .51$). No other results were significant between repetition and task ($p > .616$). Post hoc tests comparing repetition within task found that VWM vividness was better with colour repetition ($p = .003$, $d = .62$) as was VSTM ($p = .001$, $d = .78$) than without repetition. There was no effect of repetition on imagery vividness ($p = .885$, $d = .04$).

9.3.7 Comparisons with Experiment 2 data

Data was compared with that of Experiment 2 using a mixed ANOVA with the experiment as a between subjects independent variable. The analysis examined the rate of decline in performance (*d*') and vividness as set-size increased in separate mixed ANOVAs. Analysis only included conditions for which there was the same set-size. An Experiment x Set-size mixed ANOVA was completed for each task to see if there is evidence for an interaction between the experiment and set-size. In addition, capacity (*k*) data was compared with that of experiment 2 using a mixed ANOVA with the experiment as a between subjects independent variable. This analysis aimed to understand if task capacity changed depending upon experiment. Post hoc analysis using Bonferroni corrections were used to investigate significant differences. The main analysis included all participant data. Nine participants from experiment 2 and five participants from the current experiment reported using alternative cognitive strategies (e.g., 'I gave each black block a specific number to encode its location'). Statistical analysis was re-conducted with these participants removed. The main analysis is reported and analysis with participants removed are only reported if notable differences are found.

9.3.7.1 Imagination results

A 2 (experiment: objects, colours) x 4 (set-size: 3, 4, 5, 6) mixed ANOVA on imagery *d*' with experiment as a between subjects independent variable yielded an effect of set-size, $F(3, 201)=$ 50.12, $p < .001$, $\eta_g^2 = .18$, with *d*' decreasing with increase in set-size. There was no effect of experiment $F<1$, and a significant interaction effect between set-size and experiment, $F(3, 201)= 2.76$, $p = .043$, $\eta_g^2 = .01$. Post hoc analysis found no significant differences between object and colour experiments at any set-size ($p > .100$).

A 2 (experiment: objects, colours) x 4 (set-size: 3, 4, 5, 6) mixed ANOVA on imagery vividness with the experiment as a between subjects independent variable yielded an effect set-size, $F(1.65, 110.25)= 110.17$, $p < .001$, $\eta_g^2 = .19$, with vividness decreasing with increase in set-size. There was no effect of experiment $F<1$, and no significant interaction effect between set-size and experiment, $F < 1$.

9.3.7.2 VWM results

A 2 (experiment: object, colours) x 4 (set-size: 3, 4, 5, 6) mixed ANOVA on VWM *d*' with the experiment as a between subjects independent variable yielded an effect set-size, $F(3, 201)=$

47.76, $p < .001$, $\eta_g^2 = .16$, with *d*' decreasing with increase in set-size. There was no effect of experiment $F < 1$, and no significant interaction effect between set-size and experiment, $F < 1$. Different results were found for participants removed due to using alternative cognitive strategies. There was an effect of set-size, $F(3, 159) = 47.12$, $p < .001$, $\eta_g^2 = .17$, with *d*' decreasing with increase in set-size. There was no effect of experiment $F < 1$, and a significant interaction effect between set-size and experiment, $F(3, 159) = 3.61$, $p = .015$, $\eta_g^2 = .02$. Post hoc analysis found no significant differences between object and colour experiments at any set-size ($p > .189$)

A 2 (experiment: object, colours) x 4 (set-size: 3, 4, 5, 6) mixed ANOVA on VWM vividness with the experiment as a between subjects independent variable yielded an effect set-size, $F(1.89, 126.45) = 101.72$, $p < .001$, $\eta_g^2 = .17$, with vividness decreasing with increase in set-size. There was no effect of experiment $F(1, 67) = 1.46$, $p = .232$, $\eta_g^2 = .02$, and no significant interaction effect between set-size and experiment, $F(1.89, 126.45) = 2.65$, $p = .078$, $\eta_g^2 = .01$.

9.3.7.3 VSTM results

A 2 (experiment: object, colours) x 2 (set-size: 3, 5) mixed ANOVA on VSTM *d*' with experiment as a between subjects independent variable yielded an effect of set-size, $F(1,67) = 87.06$, $p < .001$, $\eta_g^2 = .22$, with *d*' decreasing with increase in set-size. There was an effect of experiment $F(1 ,67) = 5.28$, $p = .025$, $\eta_g^2 = .06$, with the object experiment producing better *d*' than the colour experiment. There was no significant interaction effect between set-size and experiment, $F < 1$. Different results were found for participants removed due to using alternative cognitive strategies. There was an effect of set-size, $F(1, 53) = 61.55$, $p < .001$, $\eta_g^2 = .21$, with *d*' decreasing with increase in set-size. There was no effect of experiment, $F(1, 53) = 2.42$, $p = .126$, $\eta_g^2 = .03$, and no significant interaction effect between set-size and experiment, $F(1, 53) = 2.68$, $p = .108$, $\eta_g^2 = .01$.

A 2 (experiment: object, colour) x 2 (set-size: 3, 5) mixed ANOVA on VSTM vividness with experiment as a between subjects independent variable yielded an effect of set-size, $F(1,67) = 99.73$, $p < .001$, $\eta_g^2 = .17$, with vividness decreasing with increase in set-size. There was an effect of experiment $F(1, 67) = 11.02$, $p = .001$, $\eta_g^2 = .12$, with the object experiment producing better vividness scores than the colour experiment. There was no significant interaction effect between set-size and experiment, $F(1, 67) = 1.50$, $p = .225$, $\eta_g^2 < .01$.

9.3.7.4 Capacity comparisons with experiment 2 data

A 2 x (experiment: object, colour) x 3 (task: imagination, VWM, VSTM) mixed ANOVA on capacity (*k*) with the experiment as a between subjects independent variable yielded an effect of task, *F*(2, 134)= 28.58, $p < .001$, $\eta_g^2 = .11$, with *k* being significantly lower in imagery than VWM ($p < .001$) and VSTM ($p < .001$), with no evidence of a difference between VWM and VSTM ($p = .999$). There was an effect of experiment *F*(1, 67)= 4.35, $p = .041$, $\eta_g^2 = .04$, with the object experiment producing higher overall *k* than the colour experiment. There was also a significant interaction effect between task and experiment, *F*(2, 134)=11.63, $p < .001$, $\eta_g^2 = .05$. Post hoc analysis found significant differences between the object and colour experiments for VSTM *k* ($p < .001$, $d = 1.15$), with capacity greater in the object experiment, with no significant differences found between the object and colour experiments for imagery *k* ($p = .589$, $d = .24$) or VWM *k* ($p = .097$, $d = .46$), see Figure 9.5.

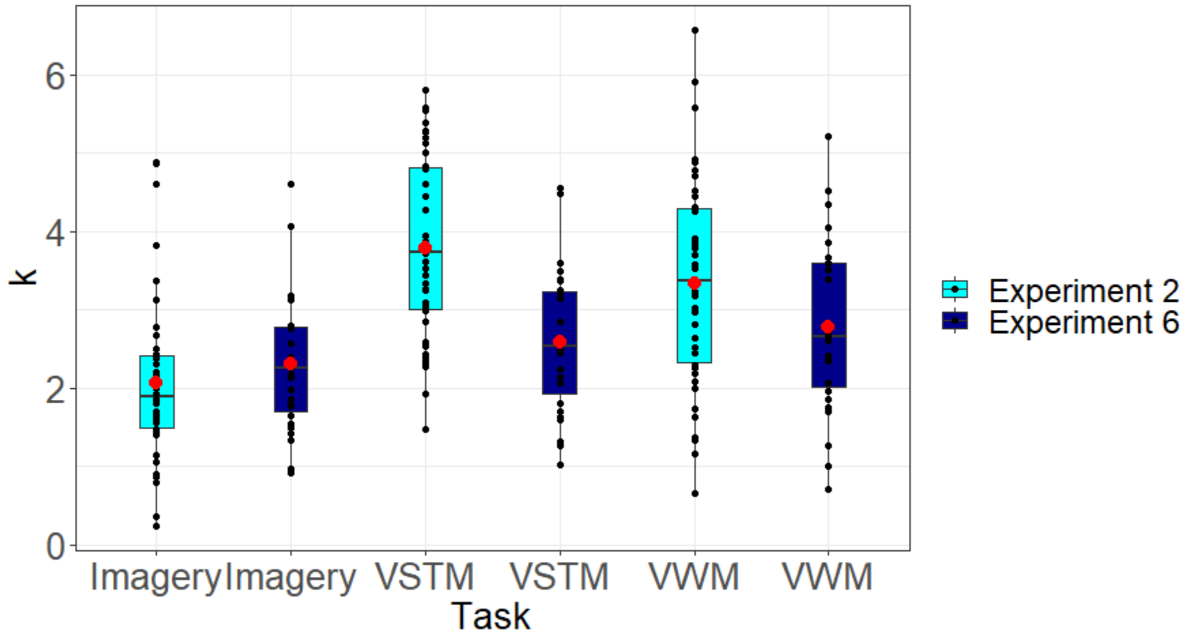

Figure 9.5. Capacity estimates (*k*) for each participant in the object experiment (Experiment 2) and colour experiment (Experiment 6) for imagination, VSTM and VWM tasks. Red dots show mean score.

9.4 Discussion

This study was designed to determine if imagery and VMst capacity are influenced by increasing object complexity by measuring the ability of participants to bind different colour to a particular location. In contrast, Experiment 2 used relatively simple stimuli (black blocks) to estimate capacity for imagery and VMst. To investigate the influence of object complexity on performance (and capacity estimates), the current experiment manipulated set-size (3-6) and colour (red, green, blue, yellow, purple and cyan) in each task (imagery, VWM and VSTM). It was not clear how imagery performance would be influenced by increase in object complexity. It was expected that imagery performance might either be 1) reduced in comparison to Experiment 2 due to the generation of coloured objects being more effortful than simply generating black blocks as in Experiment 2 or, 2) generating coloured objects in the current experiment could be no more difficult than generating objects of the same colour in Experiment 2. Furthermore, it was expected that if generation of coloured images were more effortful than generating black blocks (as in Experiment 2), then there would be an even greater performance reduction in imagery compared to the VWM task. In contrast, if generating coloured objects were no more difficult than generating black blocks then imagery performance and VWM performance should be similarly impacted by object complexity. The findings for the imagery task show similar capacity estimates to those observed in Experiment 2 with a slight increase in capacity (although non-significant). Furthermore, as in Experiment 2, imagery capacity was significantly reduced in comparison to VWM capacity. In addition, it was expected that VWM and VSTM performance would be reduced in comparison to performance in Experiment 2 with a greater performance reduction in VSTM than VWM. The findings for the VWM task show similar capacity estimates to those observed in Experiment 2 with a slight decrease in capacity (although non-significant). In contrast, VSTM performance was significantly reduced in comparison to Experiment 2. Taken together, the results of the current experiment show imagery and VWM capacity were relatively unaffected by an increase in complexity, whereas VSTM capacity was significantly reduced by the increase in complexity.

Imagination capacity

The WoMMBAT (Morey & Morey, 2011) modelled data provided estimates of *k* for imagery, VWM and VSTM, showing that imagery capacity is lower than that of VWM. These results are consistent with the findings in Experiment 2, 3, 4 and 5 which show that imagery performance is lower than VWM. No evidence of a difference was found between imagery and VSTM, or VWM and VSTM. There are a number of interpretations of what this difference between imagery and VWM signifies. The major difference between the VWM and imagery tasks is that there is no visual input from the grid during imagery. Instead, participants have to self-generate an image using top-down resources. It might be that working memory performance is better because the sensory systems involved during encoding also support maintenance and retrieval (Nyberg et al., 2000). There is considerable evidence to suggest that this is the case (Baddeley, 1999; Cattaneo et al., 2009; Postle, 2016). Although imagery can activate sensory systems (Albers et al., 2013; Dijkstra et al., 2017; Johnson & Johnson., 2014; Lee et al., 2012), it is highly unlikely that such activation is sufficient to support imagery to the extent that sensory processing supports working memory. From this perspective, it seems that the initial sensory input supports VWM, whereas imagery does not have this support because there is no sensory input during imagery.

Another explanation could be due to imagery activating the early visual cortex to a lesser extent than during visual perception. Pearson (2019) states that visual imagery and visual perception are more similar as they proceed up the visual hierarchy. Indeed, neuroimaging findings suggest that the early visual cortex is activated less in imagination than when objects are visually perceived (Pearson et al., 2015; see Bartolomeo et al., 2020 for discussion and Pearson, 2020 for reply to Bartolomeo et al., 2020). Although, activation of the early visual cortex is relatively low during imagery compared to visual perception, similar levels of pattern activity has been found between imagery, VWM and visual perception (Albers et al., 2013; Cichy et al., 2012; Lee et al., 2012). For example, Albers et al. (2013) showed that low level features can be decoded using MPVA in areas V1 and V2 for imagery and VWM stimuli. This suggests that visual imagery and VWM share a similar format in the early visual areas and that visual representations can be formed in the early visual areas using both low-level visual input and high-level input. This evidence is aligned with the argument that the early visual areas are used as a ‘dynamic blackboard’ that integrates and enables the formation of images in the mind (Albers et al., 2013; Keogh et al., 2016). It may be that a stronger visual representation is formed in the early visual areas during VWM due to the integration of bottom-up and top-down processes, whereas imagery can only use top-down processes to create and maintain a representation which could weaken the image.

It may be that separate systems, akin to the multi-component model of visual memory, explain the differences in capacity. Some authors have proposed separate systems for imagery and VWM (Logie 1995, 2003, 2011; Logie & van der Meulen 2009; Pearson 2001; Quinn & McConnell, 2006), with imagery being generated in the visual buffer (Borst, Niven, & Logie, 2012; Pearson, 2001) while the visual appearance of perceived objects are stored in a passive store, similar to that of the visual cache (Andrade et al., 2002; Cornoldi & Vecchi, 2003; Logie, 1995; 2003; 2011; Quinn & McConnell, 2006). It could be that imagery use the visual buffer to a greater extent than VWM with this system having a reduced capacity to that of the visual cache. Indeed, evidence suggests that the retinotopic architecture of early visual areas (e.g., area V1) could be the cause of capacity limitations (Franconeri et al., 2013). If the different tasks draw differentially on these systems, then this might explain differences in the capacity between imagery and VWM.

The lower capacity estimates of imagination compared to VWM could be due to the recruitment of top-down processes needed to generate and maintain an image (Dijikstra et al., 2017; Pearson, 2019; Schlegel et al., 2013). Previous research suggests that internally generated images produce more variable top-down activation patterns in comparison to visual mechanisms that use both bottom-up and top-down processes (Albers et al., 2013; Pearson, 2019). Interestingly, these top-down connections have been associated with attentional processes (Mayer et al, 2007; Zanto et al., 2011). Interestingly, Dijkstra et al. (2017) suggests that general attention load increases when images are generated internally rather than perceived. Therefore, the capacity differences between imagination and VWM could be explained by imagery generation and maintenance requiring more attentional processes than encoding and maintaining a memory.

The relationship between performance and vividness between task have been fairly consistent throughout the thesis, with vividness broadly mirroring the performance findings. Indeed, all previous experiments in this thesis found that performance and vividness was poorer in imagery than visual memory in the short-term. However, in the current experiment, vividness was similar between the three tasks (imagery, VWM and VSTM), whereas performance was lower between imagery and VWM. It is unclear why the trial-by-trial vividness ratings did not mirror the performance data in this experiment. It is possible that this is a feature of using colour stimuli.

Object complexity, imagery and VWM

The capacity estimates in the current experiment were similar to the capacity estimates found in Experiment 2 for imagery and VWM. These findings indicate that imagery and VWM are relatively unaffected by increase in complexity. This suggests that the generation of imagination/memory representations of an object is no more difficult when the objects are of increased complexity. Interestingly, it seems that imagery might be helped through items being more distinctive. Secondary analysis of set-size 4 in the imagery task showed that providing participants with a single colour repetition (e.g., imagine two blue blocks out of four) within a trial reduced performance in comparison to trials in which all colours were different. It could therefore be that generating images of the same colour in the original imagery task (using all black blocks) is more difficult to generate, and systematically harms imagination in a way in which the original VWM task does not harm VWM. However, this interpretation is based on secondary analysis and future research should aim to investigate the influence of object similarity on imagery and VMst.

The similar capacity estimates found in the current experiment and experiment 2 for VWM suggests that extra features are integrated into objects at no additional cost. In support of this, previous research has found that capacity is defined by the number of objects rather than the number of features (Luck & Vogel, 1997; Luria & Vogel, 2011). This finding provides evidence in favour of the bound object hypothesis (Luria & Vogel, 2011) rather than the independent feature stores (Shin & Ma, 2017; Wang et al., 2017; Wheeler & Treisman, 2002) which proposes that encoding multiple dimensions of a feature (e.g., discernible colours for each object) reduces performance.

Complexity and VSTM

Unlike imagery and VWM, VSTM was affected by increase in complexity. This suggests that an additional cost is associated with integrating features into VSTM. The finding supports the idea that encoding multiple dimensions of a feature reduces performance (Shin & Ma, 2017; Wang et al., 2017; Wheeler & Treisman, 2002). This finding is further supported by the secondary analysis on set-size 4 for colour repetition in the VSTM task, which showed that performance increased when colour repetition was present, demonstrating that fewer values of a feature increased performance. Furthermore, the reduction in VSTM capacity in the current experiment compared to Experiment 2 support the findings of Wheeler and Treisman (2002). Experiment 3B of Wheeler and Treisman’s (2002) study used a single-cue change detection task to investigate accuracy of colour, location and the binding of colour to location. Crucially, they found that performance was poorer in the colour-to-location binding condition in comparison to the location only condition. This finding suggest that there is a cost associated with additional features in VSTM. This finding could be explained by the focus of attention. Previous research has suggested that the focus of attention is crucial when binding information in memory (Awh & Jonides, 2001; Fougnie & Marois, 2006; Treisman & Zhang, 2006; Wheeler & Treisman, 2002; Woodman & Luck, 2004). In the VSTM task of the current experiment, it may be that the focus of attention could not be directed to each object's colour and location to bind them due to the simultaneous presentation of information (Yamamoto & Shelton, 2009).

Another explanation for the reduction in VSTM capacity in the current experiment in comparison to Experiment 2 may be due to the current experiment requiring more attentional processes. In Experiment 2 VSTM capacity was greater, and this may be due to the extraction of configural information. For example, participants might have been able to extract spatial frequency such as the global configuration of the sample display. In contrast, the current VSTM task rather requires participants to extract the spatial frequency and bind colour to the relevant location. Therefore, the current experiment may require more attentional processes than Experiment 2.

Alternatively, it could be that VSTM was affected by the lack of relational information at test. During the VSTM sample array, all items are presented simultaneously. However, at test, only a single item is presented. It could be that the lack of relational information at test affects the memory process. Indeed, results from Experiment 5 suggest that VSTM is supported by the global organisation of objects. Performance was reduced when only a single cue display was presented at test in comparison to whole and single post-cue displays. Taken together these findings support the relational information hypothesis (Alvarez, 2011) which states that objects in VSTM are interrelated and encoded together.

A difference was found for *d*' between Experiment 2 and the current experiment for VSTM with participants removed for using alternative strategies. However, the comparison between the two experiments only included set-size 3 and 5. The reason for this was that Experiment 2 used set-size 3, 5, 7 and 9 for VSTM, whereas the current experiment used set-size 3, 4, 5 and 6. Therefore, only set-size 3 and 5 could be used for direct comparisons. Interestingly, set-size 3 and 5 are relatively high performing compared to set-size 4 and 6 (Figure 9.2: top) and this explains why *k* differences remain as the modelling takes into account all set-sizes.

Limitations

Relatively simple stimuli were used across all experiments (e.g., black blocks or coloured blocks) which may explain the comparatively stable capacity estimates of imagery and VWM. Future research could use more complex stimuli (e.g., abstract shapes) and more complex conjunction stimuli (e.g., shape and orientation) to further investigate object complexity in imagery and VMst. Indeed, previous research has found that capacity estimates remains stable around 3-4 when using simple features such as colour but decreases when using more complex stimuli such as random polygons (Alvarez & Cavanagh, 2004; Brady & Alvarez, 2015; Taylor et al., 2017). It may be that a further increase in complexity could affect imagery and VWM differently.

Secondary analysis showed that colour repetition affected imagination and VMst differently. The amount of repetition in the higher set-sizes (e.g., 5 and 6) could allow for chunking and better associations between objects, which could be argued as being less about capacity and rather more about strategy. Future research should contain equal amounts of colour repetition as this will 1) enable greater understanding of capacity for visual imagery and VMst and 2) provide further understanding as to how imagery and VMst are influenced by colour repetition.

Chapter 10: Individual differences

10.1 Introduction

Data were collected across all experiments on a number of measures in order to explore the associations between them using a larger sample than in any individual experiment. Measures included those from the imagination, VWM, VSTM tasks (*d*', *k* and vividness), questionnaire measures (VVIQ, VOSI, CDQ-R, mathematical proficiency), working memory measures (Corsi tasks) and strategy questions. A single vividness and *d*' value (for each of the tasks – imagery, VWM and VSTM) was computed for each participant in each experiment, with the mean taken across experimental conditions.

10.2 Results

10.2.1 Correlations and discussion

The means and standard deviations for performance (*d*'), capacity (*k*) and vividness for each task (imagery, VWM and VSTM) across experiments (1 – 6) are reported in Table 10.1. VWM and VSTM means, across measures (*d*', *k* and vividness), are better than imagination, with VWM and VSTM providing similar means across measures. The means and standard deviations for strategy questions, questionnaire measures and Corsi block forward / backward tasks across experiments (1 – 6) are reported in Table 10.2. The means of the questionnaire measures and the Corsi block forward / backward tasks are similar to those found in the original studies (Kaufman et al., 2009; Marks, 1973; Vandierendonck et al., 2004; means and standard deviations are not reported in Blazhenkova, 2016: VOSI). Table 10.3 shows correlations between measures in the imagination, VWM and VSTM tasks (*d*', *k* and vividness) with questionnaires and Corsi forward / backward tasks (Table 10.4 shows sample size for Table 10.3 correlations). Table 10.5 presents correlations between imagination *d*', *k*, vividness rating and strategy questions (Table 10.6 shows sample size for Table 10.5 correlations). In previous experimental chapters only *d*' and *k* were correlated with questionnaires and Corsi tasks as capacity and performance were the main interest (vividness measures were used as a self-report sense check). Vividness is now included to explore the associations across measures.

Significant correlations will be presented in scatterplots to show the spread of the data. Scatter plots (Figures 10.1 – 10.6) display data for the significant correlations between tasks (imagination, VWM, VSTM) and questionnaire measures (VVIQ, VOSI, CDQ-R, mathematical proficiency) and Corsi block tasks (forward and backward). Figure 10.1 shows correlations between *k* for each task. Figure 10.2 displays correlations between *k* for each task and Corsi forward and backward. Figure 10.3 presents correlations between vividness for each task and the VVIQ. Figure 10.4 shows correlations between vividness for each task and the VOSI. Figure 10.5 displays correlations between vividness for each task and the CDQ-R. Finally, Figure 10.6 shows correlations between vividness for each task and mathematical proficiency. These correlations are also show in Table 10.3. In addition, scatter plots (Figure 10.7) display the data for significant correlations between imagination (*d*' and vividness) and strategy questions. These correlations are also shown in Table 10.5. There are numerous findings of note.

Table 10.1. Mean and standard deviations (parenthesis) for *d*', *k* and vividness for task (imagination, VWM, VSTM) across experiments (1-6).

	Imagination			VWM			VSTM		
Measure	*d*'	*k*	Vividness	*d*'	*k*	Vividness	*d*'	*k*	Vividness
	1.40 (.78)	2.31 (1.02)	2.63 (.58)	2.21 (1.02)	3.11 (1.27)	3.05 (.51)	1.86 (.75)	3.25 (1.21)	2.92 (.49)

Note. *N* = 185 for imagination *d*' and vividness, *N* = 157 for VWM *d*' and vividness and *N* = 97 for VSTM *d*' and vividness. *N* = 97 for imagination capacity (*k*), *N* = 69 for VWM *k* and *N* = 69 for VSTM *k*.

Table 10.2. Descriptive results of strategy questions (imagination), VVIQ, VOSI and subscales, CDQ-R, mathematical proficiency, forward and backwards Corsi span.

	M	*SD*	*N*
After the cues were presented, I used them as I was asked to	4.28	.64	185
I often *did not* imagine the objects	2.46	.88	185
My ability to imagine the objects were dependent on how many objects were being asked to imagine	4.41	.63	69
When tested I remembered the cues instead of thinking about the imagined objects	2.70	1.11	185
I used words and/or sentences to help myself remember	2.51	1.43	185
I used numbers to help myself remember	2.61	1.32	185
After the cues I vividly imagined the object, as if I could see it in front of me	3.30	1.03	185
Did the arrows make it possible for you to know which cell you were to imagine the object in?	4.16	.61	157
VVIQ	36.82	10.13	182
VOSI (Object vividness)	48.66	9.12	157
VOSI (Spatial vividness)	38.46	9.75	157
VOSI (Vividness Total)	87.13	17.39	157
CDQ-R Total	67.47	15.14	182
Mathematical proficiency	10.94	2.39	182
Corsi span (forward)	6.23	1.07	94
Corsi span (backward)	6.09	.82	69

Table 10.3. Correlations among imagination, VWM and VSTM (*d*’, *k* and vividness) and questionnaires: VVIQ, VOSI and subscales, CDQ-R, mathematical proficiency and forward and backwards Corsi span.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Imagery *d'*	-																
2	Imagery *k*	**.94****	-															
3	Imagery vividness	**.30****	**.26***	-														
4	VWM *d'*	**.68****	**.68****	**.16***	-													
5	VWM *k*	**.62****	**.68****	.15	**.93****	-												
6	VWM vividness	**.42****	**.41****	**.76****	**.47****	**.51****	-											
7	VSTM *d'*	**.44****	**.46****	-.12	**.55****	**.51****	.04	-										
8	VSTM *k*	**.31****	**.39****	-.09	**.43****	**.56****	.18	**.90****	-									
9	VSTM Vividness	-.02	.00	**.45****	-.04	.09	**.51****	**.32****	**.48****	-								
10	VVIQ	-.03	.09	**-.27****	.05	.17	**-.24****	.11	.12	**-.30****	-							
11	VOSI Object	.04	-.01	**.28****	.02	-.04	**.24****	-.09	-.06	**.29****	**-.74****	-						
12	VOSI Spatial	.05	.10	**.30****	.02	.02	**.27****	-.09	-.01	**.32****	**-.61****	**.70****	-					
13	VOSI Total	.05	.06	**.32****	.02	-.01	**.27****	-.10	-.04	**.33****	**-.73****	**.92****	**.93****	-				
14	CDQ-R	**.16***	.12	**.28****	.14	.08	**.33****	.00	-.12	.16	**-.32****	**.43****	**.39****	**.44****	-			
15	Mathematical proficiency	.13	.12	.09	**.18***	.14	.13	.13	.14	.16	.02	.11	**.26****	**.20***	**.20****	-		
16	Forward Corsi Span	**.36****	**.34****	**.27****	**.40****	**.30***	.23	.15	.08	-.01	-.02	-.04	.07	.02	-.10	-.17	-	
17	Backwards Corsi Span	**.37****	**.34****	.12	**.27***	.21	-.04	**.24***	.16	-.12	.10	**-.27***	-.20	**-.25***	.01	-.08	**.31****	-

Note, two-tailed test; *p < .05, ** p < .01.

Table 10.4. Sample size for each of the correlations in Table 10.3.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Imagery d'	-																
2	Imagery k	97	-															
3	Imagery vividness	185	97	-														
4	VWM d'	157	69	157	-													
5	VWM k	69	69	69	69	-												
6	VWM vividness	157	69	157	157	69	-											
7	VSTM d'	97	69	97	97	69	97	-										
8	VSTM k	69	69	69	69	69	69	69	-									
9	VSTM Vividness	97	69	97	97	69	97	97	69	-								
10	VVIQ	182	94	182	157	69	157	97	69	97	-							
11	VOSI Object	157	69	157	157	69	157	97	69	97	157	-						
12	VOSI Spatial	157	69	157	157	69	157	97	69	97	157	157	-					
13	VOSI Total	157	69	157	157	69	157	97	69	97	157	157	157	-				
14	CDQ-R	182	94	182	157	69	157	97	69	97	182	157	157	157	-			
15	Mathematical proficiency	180	92	180	157	69	157	97	69	97	177	157	157	157	177	-		
16	Forward Corsi Span	94	94	94	69	69	69	69	69	69	94	69	69	69	94	89	-	
17	Backwards Corsi Span	69	69	69	69	69	69	69	69	69	69	69	69	69	69	69	69	-

Table 10.5. Correlations for imagination *d*’, k and vividness and self-report imagination questions.

		1	2	3	4	5	6	7	8	9	10	11
1	Imagery d'	-										
2	Imagery k	**.94****	-									
3	Imagery vividness	**.30****	**.26***	-								
4	Q1 - After the cues were presented, I used them as I was asked to	.02	.14	**.24****	-							
5	Q2 - I often did not imagine the objects	**-.24****	-.16	**-.22****	**-.23****	-						
6	Q 3- When tested I remembered the cues instead of thinking about the imagined objects	**-.28****	-.20	**-.32****	**-.26****	**.36****	-					
7	Q4 - I used words and/or sentences to help myself remember	.06	.01	.13	.02	.07	**.17***	-				
8	Q5 - I used numbers to help myself remember	-.14	-.20	.02	-.06	.09	.08	**.22****	-			
9	Q6 - After the cues I vividly imagined the object, as if I could see it in front of me	**.15***	**.26****	**.32****	**.37****	**-.27****	**-.34****	-.01	-.01	-		
10	Q7 - My ability to imagine the objects were dependent on how many objects were being asked to imagine	-.12	-.11	**-.25***	-.17	.16	.12	-.05	.04	-.13	-	
11	Q8 - Did the arrows make it possible for you to know which cell you were to imagine the object in?	-.02	-.08	**.27****	**.24****	-.12	-.14	.06	-.10	**.18***	-.10	-

Note, two-tailed test; *p < .05, ** p < .01.

Table 10.6. Sample size for each of the correlations in Table 10.5.

		1	2	3	4	5	6	7	8	9	10	11
1	Imagery d'	-										
2	Imagery k	97	-									
3	Imagery vividness	185	97	-								
4	Q1 - After the cues were presented, I used them as I was asked to	185	97	185	-							
5	Q2 - I often did not imagine the objects	185	97	185	185	-						
6	Q 3- When tested I remembered the cues instead of thinking about the imagined objects	185	97	185	185	185	-					
7	Q4 - I used words and/or sentences to help myself remember	185	97	185	185	185	185	-				
8	Q5 - I used numbers to help myself remember	185	97	185	185	185	185	185	-			
9	Q6 - After the cues I vividly imagined the object, as if I could see it in front of me	185	97	185	185	185	185	185	185	-		
10	Q7 - My ability to imagine the objects were dependent on how many objects were being asked to imagine	69	69	69	69	69	69	69	69	69	-	
11	Q8 - Did the arrows make it possible for you to know which cell you were to imagine the object in?	157	69	157	157	157	157	157	157	157	69	-

Strong positive correlations were found between the three main tasks for capacity (*k*), *d*’ and vividness (Table 10.3 and Figure 10.1). This was expected given that behavioural and neuroimaging findings often find significant overlap between visual perception, imagery and visual memory (Albers et al., 2013; Chang et al., 2013; Dijkstra et al., 2017; Dijikstra et al., 2019; Ishai & Sagi, 1995; Johnson & Johnson, 2014; Keogh & Pearson, 2011, 2014; Klein et al., 2004; Lee et al., 2012; Ragni et al., 2020; Reddy et al., 2010; Schlegel et al., 2013; Pearson, 2019; Pearson et al., 2015). Furthermore, the strongest positive correlation was between imagery and VWM, followed by VSTM and VWM with the weakest between imagery and VSTM (Figure 10.1 - only *k* is presented). This pattern was true for *k*, *d*’ and vividness ratings (Table 10.3). Both imagery and VWM require storage and manipulation of information, and previous research has shown similar neural activation between the imagery and VWM (Albers et al., 2013; Johnson & Johnson, 2014; Lee et al., 2012). As such it is unsurprising that they are strongly related. Imagery correlated least strongly with VSTM in comparison to VWM which suggests that these tasks did not share as many processes. Indeed, chapter 8 and 9 have suggested that there was a significant role of configural processing in the VSTM task but not in the imagery task. In contrast, VWM may have been more related to VSTM than imagery because participants are exposed to the visual stimuli during build up in both the VWM and VSTM tasks.

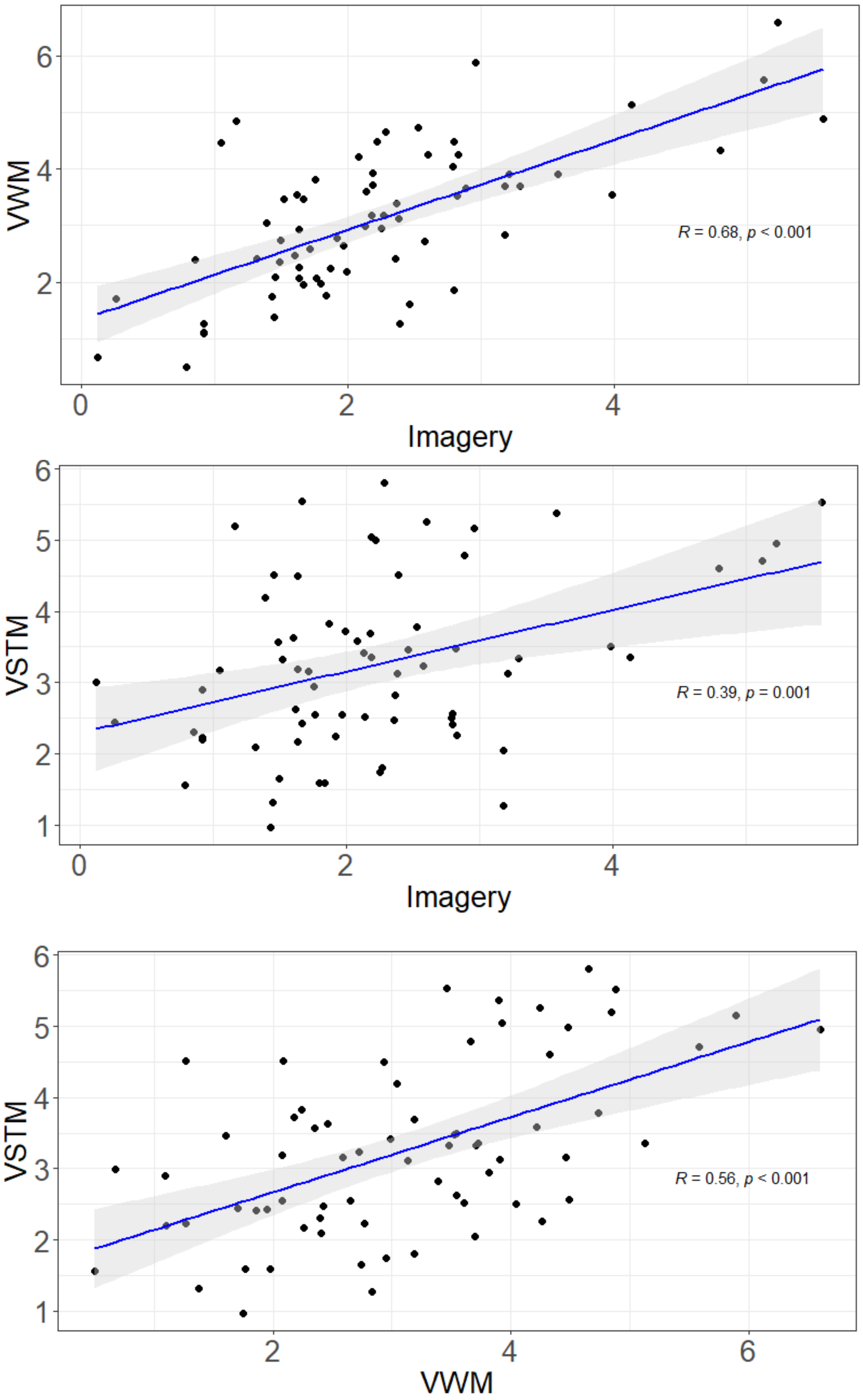

Figure 10.1. Scatterplots of capacity (*k*) estimates from imagery, VWM and VSTM tasks (*N*=69). Line of best fit is indicated including 95% confidence intervals, with the correlation value and significance shown in each plot.

Interestingly Corsi span score (Forward and Backwards) correlated more strongly and reliably with imagination capacity than it did with VWM (Figure 10.2). This is surprising given that Corsi span is understood to be a measure of working memory capacity. However, evidence suggest that Corsi tasks are not pure measures of working memory as they tap into multiple resources and processes (e.g., Donolato et al., 2017). Critically, the Corsi task requires reconstruction of the sequence in which blocks were highlighted in the mind's eye. In contrast, in the VWM task presented here, the sequence was not task relevant even though it might have been encoded as part of a memory strategy. Thus, these correlations suggest that the reconstruction of a dynamic event is consistent with a dissociation from maintenance and storage and may be related more to imagery. Given the imagery task was not dynamic, it may be that it is the generative component of imagery that underpins sequence reconstruction in the Corsi task. Interestingly, only imagination *k* was significantly positively correlated with the Backwards Corsi span score (Figure 10.2). This could be due to the Backwards Corsi task and the imagery task utilising more executive processes than the Forward Corsi task and the current studies VWM and VSTM tasks. This idea is supported in the literature with Backward Corsi recall being associated with executive control (Hester et al., 2004; Higo et al., 2014; although see, Donolato et al., 2017) and imagery generation and maintenance using a mechanism similar to that of the central executive (Albers et al., 2013; Dijkstra, et al., 2017; Logie, 1995). It could therefore be that both the imagination task and the Backwards Corsi task tap into executive processes.

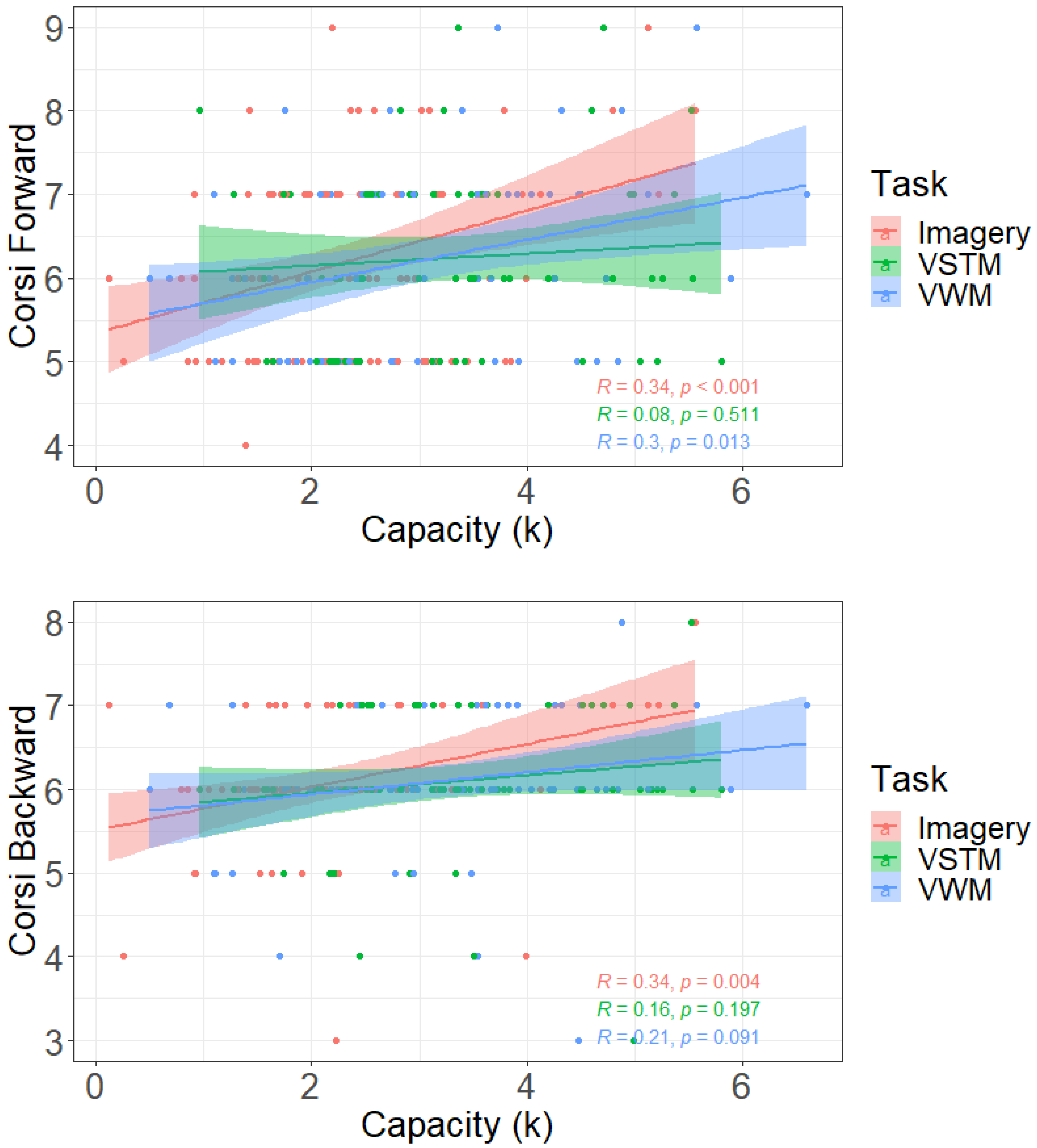

Figure 10.2. Correlations between capacity (*k*) in different tasks (imagery, VSTM, VWM) and Corsi Span (Forward, Backward). Red/blue/green dots refer to data from imagery/VWM/VSTM respectively. Colours of the lines of best fit (including 95% confidence intervals) follow the respective dot colours. Imagery and VWM capacity were significantly correlated with Corsi Span Forward (top). Only imagery capacity was significantly correlated with Corsi Span Backwards (bottom).

Figure 10.3 shows strong negative relationships were found between *vividness* ratings in all three main tasks and the VVIQ (Marks, 1973). However, note that a numerical negative correlation is a conceptual positive correlation here. The VVIQ is widely used and is considered a standard measure of assessing images in the mind (Borst & Kosslyn, 2010; Fulford et al., 2017). However, the measure often produces mixed results, with the direction of the relationship often dependent upon the type of task used (Friedlander et al., in review; McKelvie, 1995; for review, see McAvinue & Robertson, 2007). In addition, similar to the VVIQ findings, strong positive associations were found between *vividness* ratings in all three tasks and the VOSI (Figure 10.4; Blazhenkova, 2016). Taken together, these findings validate the VOSI and the VVIQ as being reliable measure of object and spatial imagery/memory. The significant overlap between tasks and the VVIQ and the VOSI correlations further support the findings that imagery and memory in the short-term share some underlying processes (e.g., Albers et al., 2013; Lee et al., 2012; Reddy et al., 2010).

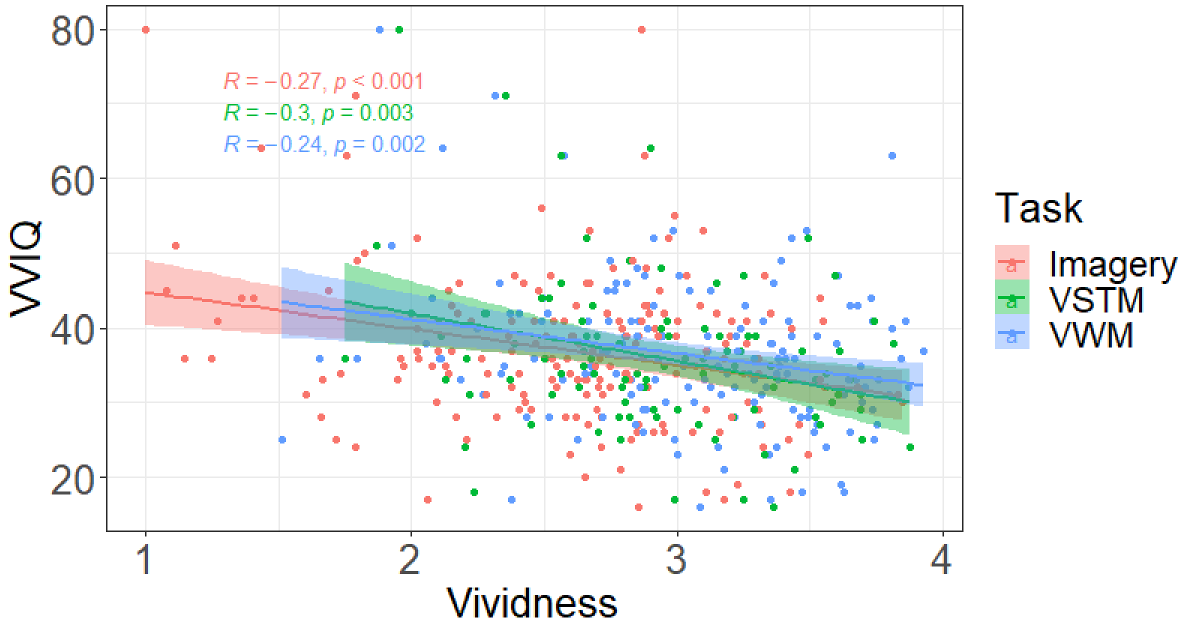

Figure 10.3. Correlations between task vividness (imagery, VSTM, VWM) and the VVIQ. Red/blue/green dots (and respective lines of best fit with 95% confidence intervals) refer to data from imagery/VWM/VSTM respectively. All three tasks were negatively correlated with the VVIQ. Sample size varies between task (imagery, *N* = 182, VSTM, *N* = 97, VWM, *N* = 157).

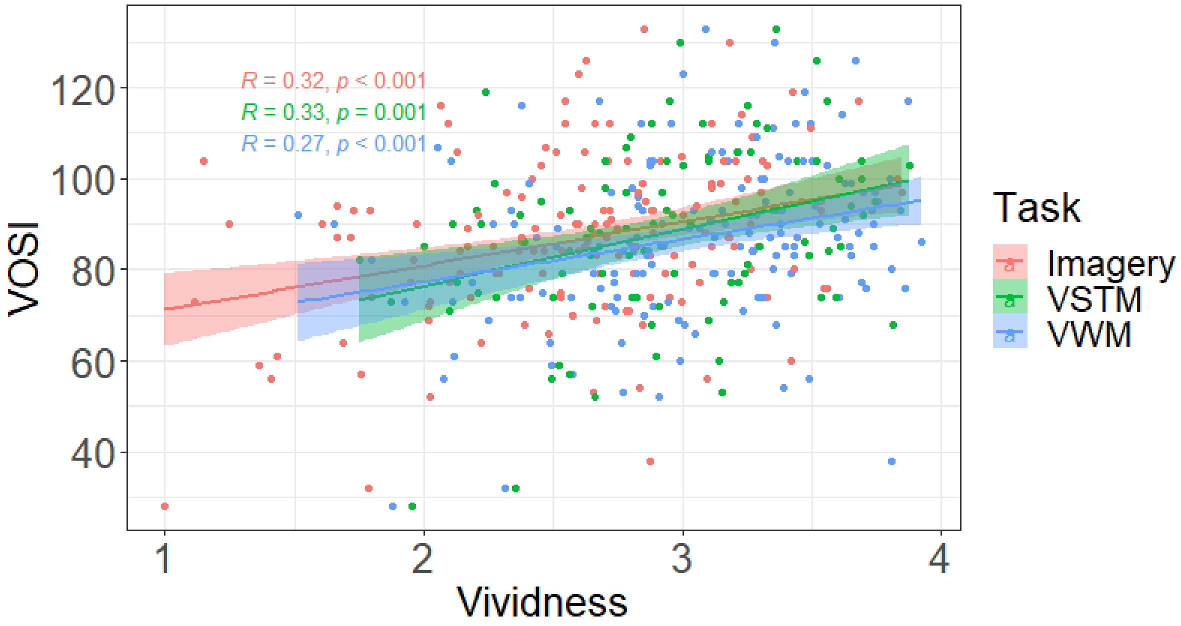

Figure 10.4. Correlations between task vividness (imagery, VSTM, VWM) and VOSI. Red/blue/green dots (and respective lines of best fit with 95% confidence intervals) refer to data from imagery/VWM/VSTM respectively. All three tasks were positively correlated with the VOSI. Sample size varies between task (imagery, *N* = 157, VSTM, *N* = 97, VWM, *N* = 157).

Figure 10.5 shows the relationships between task and the CDQ-R (Kaufman et al., 2009). A positive association was found between vividness for imagination and VWM and the CDQ-R. There is a considerable field of research indicating that images in the mind and creativity are inextricably intertwined (for review, see Abraham, 2016). In contrast, other research has found the relationship between the two be less clear (Kozhevnikov et al., 2013; LeBoutillier & Marks, 2003). If, however, creativity is to be described as an ability to produce novel or original work (Feist, 1998; Runco & Jaeger, 2012), then the positive association found here is intuitive, given that the imagery and VWM tasks required participants to build-up novel images of black blocks, which were either self-generated or perceived (Imagery and VWM, respectfully).

Interestingly this building up seems to be critical, as there was no correlation with the VSTM task in which there was no build-up of stimuli.

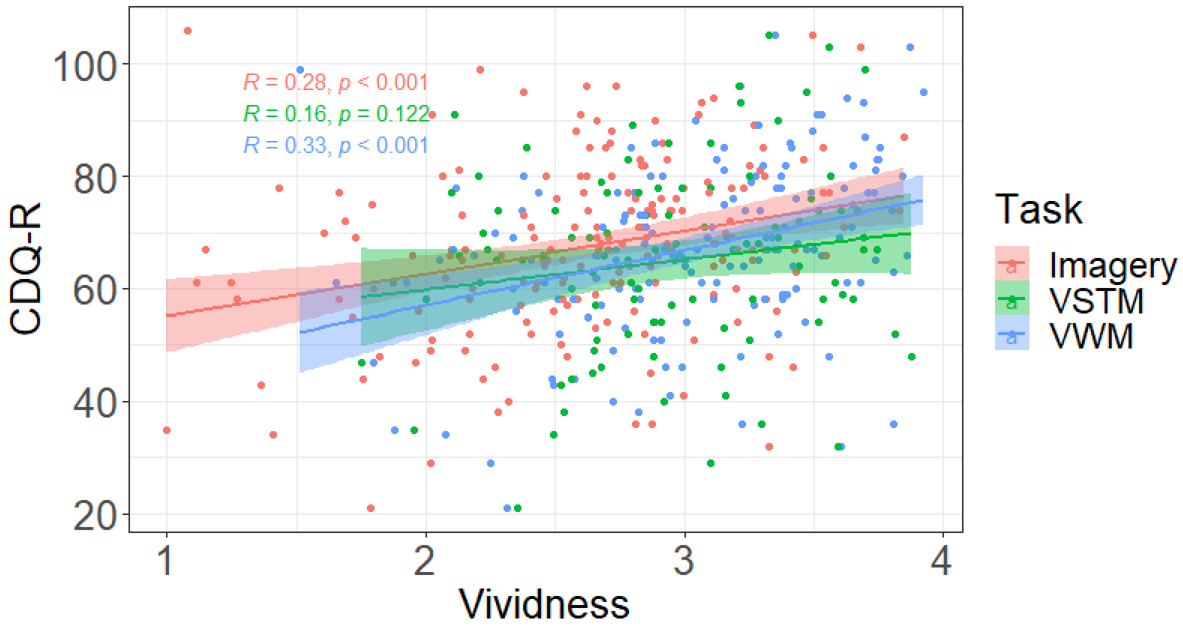

Figure 10.5. Correlations between task vividness (imagery, VSTM, VWM) and the CDQ-R. Red/blue/green dots (and respective lines of best fit with 95% confidence intervals) refer to data from imagery/VWM/VSTM respectively. Only Imagery and VWM positively correlated with the CDQ-R. Sample size varies between task (Imagery, *N* = 182, VSTM, *N* = 97, VWM, *N* = 157).

Figure 10.6 shows the relationship between task and mathematical proficiency. The only significant positive correlation was between VWM *d*' and mathematical proficiency. This finding is in keeping with the literature between working memory and mathematical ability (for review, see Raghubar et al., 2010). However, it is important to note that correlations across all three tasks were positively correlated, and the significant correlation with VWM was only marginally significant. Therefore, it is difficult to draw firm conclusions from the findings here about the role of VWM in mathematical proficiency.

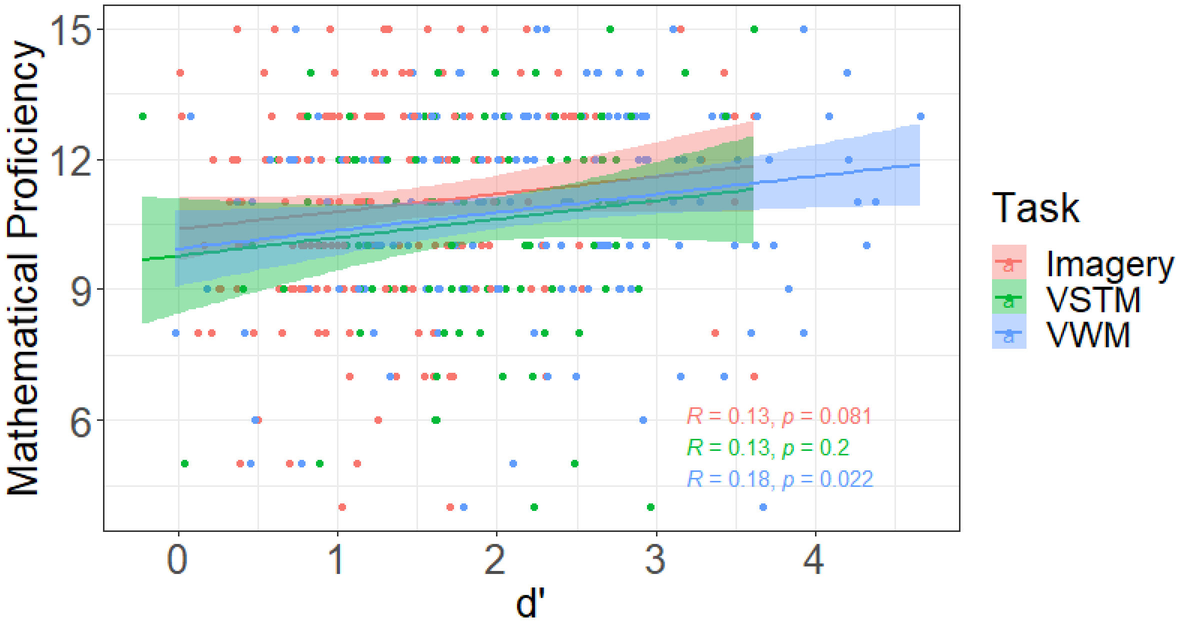

Figure 10.6. Correlation results between task *d*' (imagery, VSTM, VWM) and Mathematical Proficiency. Each dot shows an individual participant. Red/blue/green dots (and respective lines of best fit with 95% confidence intervals) refer to data from imagery/VWM/VSTM respectively. Only VWM *d*' positively correlated with Mathematical Proficiency. Sample size varies between task (Imagery, *N* = 180, VSTM, *N* = 97, VWM, *N* = 157).

Finally, there are numerous findings regarding the relationship between the imagination task and strategy questions (Figure 10.7). There was a positive relationship between imagination vividness and the strategy question 'After the cues were presented, I used them as I was asked to' (Figure 10.7: panel D), indicating that using the cues as asked benefited performance. Indeed, if participants used the cues in other ways (e.g., visually recalled the cues, instead of imagining an object at the cued location) then this could disrupt imagery, which has been shown to be the case in previous research (e.g., Borst, Ganis et al., 2012). Further support for this interpretation is found by the strong negative correlation between imagination (*d*' and vividness) and the question 'When tested I remembered the cues instead of thinking about the imagined objects' (Figure 10.7: panel B; only *d*' is presented). A negative association was found between imagination (*d*' and vividness) and the question 'I often did not imagine the objects' (Figure 10.7: panel A; only *d*' is presented). This finding indicates that imagining objects rather than employing another strategy to perform the imagination task, benefits imagery vividness and performance. A strong positive correlation was found between imagination (*d*', *k*, and vividness) and the question ‘After the cues I vividly imagined the object, as if I could see it in front of me’ (Figure 10.7: panel C; only *d*' is presented). This suggests that participants who could clearly imagine the object performed better in the task, indicating that self-reported vividness introspection is predictive of performance. In addition, a negative association was found between imagination vividness and the question ‘My ability to imagine the objects were dependent on how many objects were being asked to imagine’ (Figure 10.7: panel E). This suggests that vividness was reduced when an increasing number of objects were to be imagined. This finding is also in keeping with the self-reported vividness ratings in Experiments 1, 2 and 6 which showed that vividness decreased with increase in set-size. These results suggest that participants had good metacognition of their imagery. Finally, a positive relationship was found between imagination vividness and the question ‘Did the arrows make it possible for you to know which cell you were to imagine the object in?’ (Figure 10.7: panel F). This finding suggests that vividness was reduced if the participant was less sure about the location of the to-be-imagined object. Overall, these findings suggest that the imagination task was a valid measure of imagery.

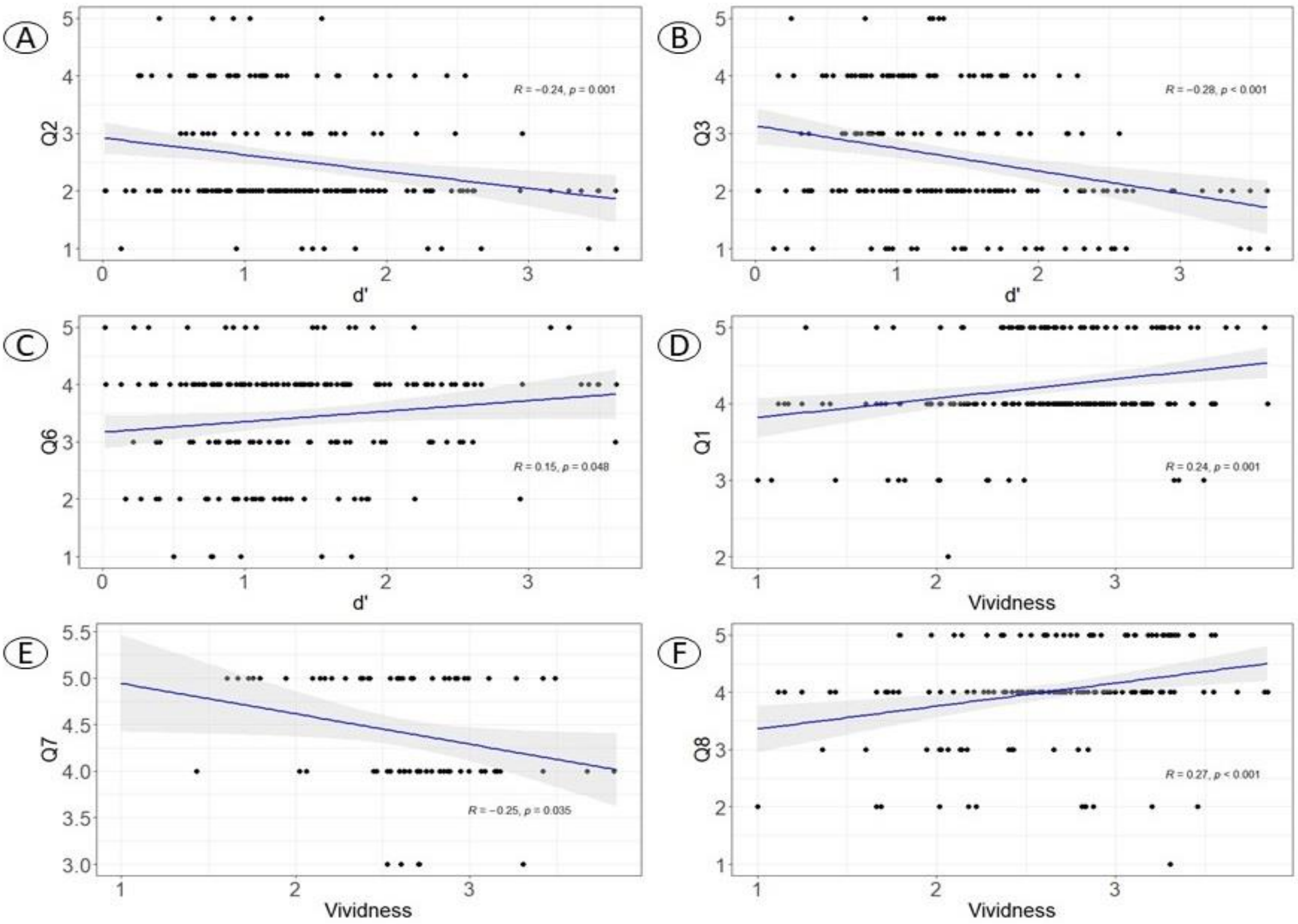

Figure 10.7. Correlations between imagery and strategy questions. Each dot shows an individual participant with a line of best fit (with 95% confidence intervals) fitted through the data. Panel A: shows a negative association between imagination d’ and question 2 (Q2 - I often did not imagine the objects). Panel B: shows a negative correlation between imagination *d*’ and question 3 (Q3 - When tested I remembered the cues instead of thinking about the imagined objects). Panel C: shows a positive correlation between imagination *d*’ and question 6 (Q6 - After the cues I vividly imagined the object, as if I could see it in front of me). Panel D: shows a positive relationship between imagination vividness and question 1 (Q1- After the cues were presented, I used them as I was asked to). Panel E: shows a negative association between imagination vividness and question 7 (Q7 - My ability to imagine the objects were dependent on how many objects were being asked to imagine). Panel F: shows Finally, a positive relationship between imagination vividness and question 8 (Q8 - Did the arrows make it possible for you to know which cell you were to imagine the object in?). Sample size varies between question and measure (See Table 10.6 for details).

Chapter 11: General discussion

11.1 Introduction

The general aim of this thesis was to explore the capacity of imagination and explore the extent to which this was similar to that of visual working memory, and thus the extent to which imagery and visual working memory were the same or different. Prior research that has investigated imagination and its limits had some significant limitations, notably in the seminal work of Keogh and Pearson (2017). Their task measured only the impact imagery had on a secondary task, performance measures were used to imply capacity limits, and stimulus specific information (e.g., colour and orientation) was used at the to-be-imagined location. Other work on the neural basis of imagination and visual working memory initially presented participants with images to be later imagined or remembered (e.g., Albers et al., 2013, Johnson & Johnson, 2014; Lee et al., 2012). Consequently, using a paradigm that measures only the impact imagery had on a secondary task does not test what is actually being represented and cannot be used to estimate capacity (Keogh & Pearson, 2017), while providing stimulus specific information or presenting stimuli means that what is being measured is some form of memory (e.g., mnemonic processing) (Albers et al., 2013; Johnson & Johnson, 2014; Keogh & Pearson, 2017; Lee et al., 2012). In a series of 6 experiments, this thesis addresses these limitations using a novel and original approach. Experiments 1-2 established the paradigm on which the thesis was based. The novel paradigm was created to provide capacity estimates for imagination and visual working memory using a similar task, but without requiring perceptual input for the former. This provides one of the strongest tests of the relation between these two cognitive processes to date. Participants were presented with a grid within which squares turned black sequentially (visual working memory), simultaneously (visual short-term memory), or they were cued to turn them black (visual imagery). The number of black blocks was manipulated to obtain capacity estimates from each task. Experiments 3-5 then explored whether the findings from Experiments 1-2 could be explained by aspects of the methodology. The final experiment extended the findings of Experiment 1-2 by examining whether imagination and visual memory in the short-term capacity were influenced by object complexity.

Together the set of experiments has provided the most comprehensive set of behavioural experiments to date that investigates the relationship between imagination and short-term visual memory within a paradigm that allows for comparable assessment of performance across imagination and memory tasks. In addition, this collection of experiments have created new knowledge by showing how the underlying processes of imagination and visual memory are different as well as similar. Finally, these experiments provide an original contribution by assessing the importance of the initial sensory input in supporting VWM capacity. These contributions will be explored later in the general discussion. The findings of each Experiment are now addressed in turn.

11.2 Summary of findings

Experiment 1 aimed to determine if capacity of VWM is the same or different to that of imagination. This experiment found that imagination is severely capacity limited (~2) compared to typical estimates (~4) of VWM capacity. However, a celling effect was found in the VWM data and so capacity estimates could not be determined for VWM task used in this experiment. Experiment 2 explored the capacity of imagination and visual memory in the short-term (VWM and VSTM), addressing issues with Experiment 1 by modifying the VWM task such that each black block was presented for 2000ms before disappearing, rather than presenting black blocks for the duration of the sample array. In addition, Experiment 2 used a post-cue at test to query a single item instead of querying the whole display at test as in Experiment 1. This reduced decisional processes to one item whilst keeping imagery/memory load consistent with Experiment 1. The change of test array also rectified issues with whole display data (see Morey, 2011). The data here showed that imagination capacity was lower than that of VWM and VSTM, with VSTM capacity similar to that of VWM. Taken together these results suggest that imagination and VMst may involve similar processes but that they are not identical.

Given the paradigm developed in Experiment 1-2 was novel, Experiments 3-5 explored whether the differences in capacity observed between imagination and VWM/VSTM in Experiment 2 could be explained by methodological factors including; the time taken to generate an image (Experiment 3), attentional factors relating to the use of arrow cues to indicate where to generate an image (Experiment 4) and whether the decision at test inadvertently supported performance in the VWM/VSTM tasks (Experiment 5). Experiment 3 investigated if the time available to generate and maintain an image is more effortful and time consuming than encoding and maintaining a memory. As per prior work (Keogh & Pearson, 2017), imagery generation and maintenance was not influenced by extended presentation time. Similarly, VWM was not influenced by extended presentation time. Critically, performance differences remained between the two tasks with visual imagery performance being poorer than that of VWM. These findings suggest that the capacity differences found between imagination and VWM in Experiment 2 cannot be explained by imagery processes needing more time to generate and maintain and image relative to VWM.

Experiment 4 explored the cuing methodology used in the imagination task in order to understand if the arrow cues selectively impaired imagery performance. In both the imagination and VWM tasks, the number of locations (6 x 6, 4 x 4) and the size of the global grid (large, small) were manipulated. This assessed if the differences found in Experiment 2 between imagination and VWM could be explained by the arrow cues directing attention away from the to-be-imagined location and thus increasing noise in the visualised object. In addition, two additional imagination conditions were introduced, which presented the arrow cues further away from the point of imagination. This aimed to understand if diverting attention further from the to-be-imagined location influenced performance. Finally, an additional VWM condition presented arrow cues simultaneously with the build-up of black blocks in order to investigate if arrow cues draw attention away from location. Taken together, the data here showed that the cueing methodology did not selectively impair imagery performance. Additionally, imagination and VWM were similarly influenced by the same manipulations (i.e., number of locations and global grid size). Furthermore, imagination performance was poorer than VWM across all comparable conditions. These results suggest that the use of arrow cues in the imagination task did not selectively impair imagination performance.

Experiment 5 aimed to determine the influence of test array on imagination, VWM and VSTM. There were three types of test display: all five black blocks (whole display), all five black blocks with one block highlighted white (post-cue display) or a single black block (single cue display). These manipulations aimed to understand if the presence of items at test reduced performance in imagery more than visual memory in the short-term. This experiment showed that VWM performance was better in the single cue test array than the post-cue and whole display test array conditions. The reverse was true for VSTM: post-cue and whole display test arrays showed similar performance levels with performance being poorest in the single cue condition. In contrast, imagery performance was relatively unaffected by test array manipulation. Critically, overall imagery performance was poorer than VWM and VSTM. However, performance levels were similar between imagination and VSTM in the single cue condition. These results show that different mechanisms and processes underpin imagery, VWM and VSTM.

Experiment 6 explored the influence of object complexity on the capacities of imagination and visual memory in the short-term. Object complexity was introduced by adding colour to the to-be-imagined or to-be-remembered block and binding this colour to a specific location. At test, one of the previous cued / presented colours were presented in the same location or differed such that the colour of the presented block was randomly selected from other colours previously visualised/remembered. The data here showed that imagination capacity was lower than that of VWM, but similar to VSTM. Furthermore, capacity estimates were similar between VWM and VSTM. Further analysis was conducted between the capacity estimates from Experiment 2 and Experiment 6. It was found that imagery and VWM were relatively unaffected by the increase in complexity whereas VSTM capacity was lower in Experiment 6. It is hypothesised that this was due to the attention required for binding in the VSTM task reducing the amount of attentional resource that could be distributed amongst all objects as well as reducing the benefit of any configural processing. Interestingly, secondary analysis on colour repetition found that when a colour repetition (e.g., two green blocks out of four coloured blocks) was present within a trial, imagery performance was reduced, whereas the lack of repetition improved performance in VSTM. Furthermore, imagery performance was reduced relative to VWM when colour repetition was presented within a trial. This is an important observation given that all blocks were the same colour in Experiment 2. Taken together these results suggest that imagination capacity is consistently lower than that of VWM. It may be that the reduced capacity of imagination relative to VWM in Experiment 2 may partially be caused by colour repetition.

The individual differences chapter explored the association between imagination, VWM, VSTM, questionnaires and Corsi block tasks across experiments. The data here show that the imagination, VWM and VSTM tasks are strongly positively associated with each other, with the strongest correlation between imagination and VWM, and weakest correlation between imagery and VSTM. This suggest that that imagination, VWM and VSTM share some of the same processes, with imagination and VWM sharing more processes than between imagery and VSTM, and between VWM and VSTM. Additionally, vividness in each task negatively correlated with the VVIQ (note, a numerical negative correlation is a conceptual positive correlation) and positively correlated with the VOSI. These findings indicate that the VVIQ and the VOSI seem to be reliable and valid measures of spatial and object imagery. A positive association was found between vividness for imagination and VWM and the CDQ-R. This suggests that creativity and construction of novel images in the mind are related. VWM *d*’ positively correlated with mathematical proficiency. It is difficult to draw a firm conclusion from this finding as the correlation was weak. Imagination vividness and performance correlated with imagination strategy questions (indicating that participants who completed the task as they were asked performed better). These findings provide evidence that the imagination task is a valid measure of imagination. Finally, strong positive correlations were found between imagination and VWM capacity and the Forward Corsi block task. However, only imagination capacity positively correlated with the Backwards Corsi block task. These findings suggest that imagination, VWM and VSTM do not use identical processes.

11.3 General discussion

11.3.1 Imagination and visual memory in the short-term: One and the same?

This thesis aimed to determine whether imagination capacity was similar to that of VWM capacity. Prior neuroimaging and behavioural research indicates that imagery, visual perception and visual memory are highly related processes (Albers et al., 2013; Chang et al., 2013; Cichy et al., 2012; Dijkstra et al., 2017; Ishai & Sagi, 1995; Johnson & Johnson, 2014; Keogh & Pearson, 2011, 2014; Klein et al., 2004; Lee et al., 2012; Pearson et al., 2015; Ragni et al., 2020; Reddy et al., 2010; Schlegel et al., 2013; for review see Pearson, 2019). Indeed, this thesis adds significant knowledge to this area of research by providing evidence that imagination and visual memory are related process, but they are not underpinned by identical processes.

Two visual memory tasks were used as estimates of visual memory, the VWM task which required manipulation of the memory by sequentially building up the stimulus to be remembered and a VSTM task, in which the stimulus was presented simultaneously, and no manipulation was required. One imagination task was used as an estimate of imagination. Similar to the VWM task, the imagination task required generation and manipulation of the image by sequentially building up the stimulus to be imagined. Data from Experiment 2 (objects) and Experiment 6 (object complexity) showed that imagery had consistently lower capacity than the VWM task, which was the most similar to the imagery task. In contrast, although imagery showed reduced capacity relative to the VSTM task in Experiment 2, capacity for imagery and VSTM were equivalent in Experiment 6. Although Experiments 3-5 did not measure capacity per se, they explored methodological factors that might have accounted for the differences in capacity observed in Experiment 2. Data showed that imagery performance and VWM performance showed very similar trends across Experiments 3-5. This was not the case for the VSTM task for reasons discussed below.

The data from Experiment 1-2 show that imagination capacity is lower than that of VWM and VSTM with capacity being similar between the memory tasks. This suggests that imagination and visual memory use different processes and mechanisms, contrasting with literature that finds similar neural activations between the two processes (e.g., Albers et al., 2013).

The findings from Experiment 3 in this thesis show that extending duration time - by allowing for longer generation / encoding and maintenance of items – had no effect on imagery and VWM, supporting the idea that imagery and VWM are related processes. This finding further suggests that imagery generation and VWM encoding occurs within 2 seconds, with previous evidence suggesting that imagery generation occurs within 1 second and VWM encoding occurring within 50 - 1000ms (for imagery see Pearson et al., 2008; for VWM see Alvarez & Cavanagh, 2008; Brady et al., 2016; Guest et al., 2015; Ricker & Cowan, 2014; Vogel et al., 2006).

Experiment 4 provides evidence that the cuing methodology did not selectively limit the performance in the imagination task. In addition, the visual arrangment of the stimuli (i.e., manipulation of grid size and number of locations) influnced imagery and VWM similarly (note VSTM was not part of this experiment), which further highlights processing similarlites between imagery and VWM. Taken together, Experiments 3 and 4 provide strong evidence for imagery and VWM being strongly related processes as they seem to be similarly influenced by the manipulations in these experiments.

The data from Experiment 5 show that imagination, VWM and VSTM were influenced differently by test array presentation. This evidence demonstrates that VWM performance was better when a single cue was presented at test, rather than when all items were presented (post-cue and whole display), which provides support for the idea that in VWM, objects are encoded independently (Woodman et al, 2012). On the contrary, VSTM performance benefited when all items were presented at test, suggesting that VSTM benefits from using relational encoding rather than independent encoding of items (Alvarez, 2011; Brady & Alvarez, 2011). In contrast no significant effect of test array was found on imagination performance, indicating that there was no configural benefit or any clear evidence for a predominance of independent item coding. Taken together, these findings imply that when items are built sequentially and require manipulation as in the imagination and VWM tasks here, then participants cannot make use of relational coding. Indeed, the data show that relational information appears to hinder performance in the VWM task. Conversely, when information is presented simultaneously and does not require active manipulation as in the VSTM task here, then relational encoding can improve performance. Interestingly, performance in the single cue condition in the imagination and VSTM tasks were similar, indicating that VSTM performance falls back to imagination levels when use of relational information at test is not possible. It is possible then, that the capacity differences found between imagination and VSTM in Experiment 2 could be a result of VSTM using relational encoding. In Experiment 2, all items were presented at test, and a single cue cued location. In this instance, VSTM was able to use relational encoding to boost capacity. Indeed, evidence suggests that content and organisation of visual information are key in understanding capacity as these aspects can have a direct impact on capacity (Balcock & Clegg, 2010; Jiang et al., 2000; Lecerf & De Ribaupierre, 2005; Yang et al., 2015).

Experiment 6 data showed that increasing object complexity (i.e., location and colour) did not reduce imagination and VWM capacity relative to Experiment 2. In contrast, VSTM capacity was significantly reduced in comparison to Experiment 2 with imagination and VSTM capacity being similar between the two tasks. The significant drop in capacity of VSTM in Experiment 6 can also be explained in terms of reflecting the importance of relational information. In Experiment 6, a single cue was used to cue colour and location and so VSTM was not able to use relational information to the same extent as it was able to in Experiment 2 and 5. Furthermore, in Experiment 2, VSTM was able to rely on the similarity (i.e., all black blocks) of the simultaneously presented items during the sample array. It is possible that participants were able to increase capacity by extracting low-level spatial frequency information (i.e., location). Conversely, the VSTM task in Experiment 6 required participants to bind information, which potentially requires more focused attention than in Experiment 2 tasks. As stimuli were presented simultaneously in the VSTM task, this required greater spread of attentional resources relative to the imagery and VWM tasks in which the stimulus build-up was sequential. In line with this view, evidence suggests that focused attention is important for binding visual information in memory (Awh & Jonides, 2001; Fougnie & Marois, 2006; Oh & Kim, 2004; Triesman & Sato, 1990; Treisman & Zhang, 2006; Woodman et al., 2001; Woodman & Luck, 2004; Wheeler & Triesman, 2002). This could explain why VSTM capacity was reduced to similar levels as that of imagination in Experiment 6.

The findings from Experiments 3, 4 and 6 suggest that imagination and VWM are very similar, and rely on the same set of processes, because the various manipulations within these experiments impacted them similarly. Nevertheless, there was a clear difference in capacity found between imagination and VWM in Experiments 2 and 6, indicating that they may not be underpinned by identical processes, despite some commonality in terms of underlying neural activation in the visual system (e.g., Albers et al., 2013). There are four potential explanations for why capacity in imagery was lower than that of VWM.

The major difference between imagery and VWM in the paradigm used here is that there is no perceptual input from the grid location during imagery. Instead, the image has to be self-generated in a top-down manner. Interestingly, similar cortical activation is elicited when encoding and retrieving the same information (Nyberg et al., 2000). This indicates the importance of the sensory systems in supporting maintenance and rehearsal (Baddeley, 1999; Cattaneo et al., 2009; Postle, 2016). Although, imagery can activate sensory systems (Albers et al., 2013; Dijkstra et al., 2017; Lee et al., 2012) this appears to be insufficient to enable robust representations of multiple items to be created and maintained. This explanation is aligned with that of grounded cognition, specifically the account of modal simulations (for review of grounded cognition, see Barsalou, 2008). Modal simulation is the re-enactment or simulation of an experience (i.e., thinking about how the test array looks in comparison to the previously presented sample array). In order to do this, brain states across modalities (perception, motor, introspection) are integrated to recreate the representation. This creates a simulation as the brain tries to recreate the activity state it was in when experiencing the sensory simulation (Barsalou 1999, Decety & Grezes 2006). It is possible then, that the initial sensory input is supporting VWM, whereas imagery does not have the initial sensory input to assist the process.

The lower capacity of imagination compared to VWM found in Experiments 2 and 6 could also be due to imagery activating the early visual cortex to a lesser extent than during visual perception. Indeed, evidence suggests that the processes of imagery and visual perception are more similar further up the hierarchy of visual processing (Pearson, 2019). Comparable levels of activity are seen between imagery and visual perception in the ventral temporal lobe, but less comparable activity is seen in the early visual areas (Pearson et al., 2015; see Bartolomeo et al., 2020 for discussion and Pearson, 2020 for reply to Bartolomeo et al., 2020). Although activation remains low during imagery, it seems that the overall pattern activity is similar between imagery, visual perception and VWM (Albers et al., 2013; Cichy et al., 2012; Lee et al., 2012). Indeed, it is possible that the early visual cortex plays an important role in both imagination and VWM as low-level features (e.g., stimulus orientation) of imagery and VWM have been decoded from the early visual cortex. It may well be that the early visual cortex is used as a ‘dynamic blackboard’ that integrates bottom-up visual input and or higher-level input to form visual representations (Albers et al., 2013; Keogh et al., 2016). It is possible that VWM benefits more from the integration of bottom-up and top-down processes as this creates stronger activation in the early visual areas. In contrast, visual imagery is solely dependent on top-down processes to generate and maintain visual representations, leading to a weaker visual representation in the early visual areas.

Another explanation of the capacity differences could be due to imagination and VWM using separate systems (Logie 1995, 2003, 2011; Logie & van der Meulen 2009; Pearson 2001; Quinn & McConnell, 2006). Evidence suggests that imagery is generated in the visual buffer (Borst, Niven, & Logie, 2012; Pearson, 2001), while perceived objects are stored in the visual cache (Andrade et al., 2002; Cornoldi & Vecchi, 2003; Logie, 1995; 2003; 2011; Quinn & McConnell, 2006). It may be that imagery relies more on the active visual buffer than VWM, with this system being more capacity limited than the passive visual cache. Indeed, the retinotopic structure of early visual areas may give rise to the capacity limitations (Franconeri et al., 2013). It is possible then, that these systems have discrete capacity limits. Future research should aim to test these systems and the interplay between them, in order to understand the importance of them in imagery and VWM capacity, and to further understand theoretical accounts of imagery and VWM.

The recruitment of top-down processes needed to enable the generation and maintenance of internally generated images (Dijikstra et al., 2017; Pearson, 2019; Schlegel et al., 2013) might be another explanation for the lower capacity estimate of imagination than VWM found in this thesis. Internally generated images may produce more variable activation patterns and are less robust than activations associated with bottom-up visual mechanisms such as in visual working memory (Albers et al., 2013; Pearson, 2019). As such, evidence suggests that more top-down processing is required during imagery in comparison to stimulus driven systems (Dijkstra et al., 2017) and these top-down connections have been found to be associated with attentional processes (Mayer et al, 2007; Zanto et al., 2011). Dijikstra et al. (2017) investigated imagery and visual perception using dynamic causal modelling (DCM) and found differences in connectivity. Stronger BOLD coupling activations from top-down connections were found when imagining objects relative to perceiving objects. This could be due to the extra attentional resources needed to generate and maintain imagined experiences in the absence of visual input (Dijikstra et al., 2017). Therefore, the lower capacity of imagination compared to VWM could reflect an increase in attentional load that is associated with the self-generation and maintenance of images. However, it should be noted that Experiment 3 allowed for extra time to generate and maintain items, but this had no effect on performance, which suggests that greater use of executive / attention resources when imagining may not explain the difference in capacity observed here.

This thesis presents six different experiments which manipulate different aspects of the tasks to see if this affected behaviour. The number of objects (Experiments 1 and 2), duration time (Experiment 3), visual arrangements of the stimuli (Experiment 4), configuration of test array (Experiment 5) and complexity (Experiment 6) were all manipulated in an attempt to tease apart the processes of imagination and VMst. Taken together, the findings suggest that imagination and VWM are very similar with the explanations above accounting for the capacity differences. In contrast, it appears that different processes and mechanisms underpin imagination and VSTM (e.g., relational processing). Nonetheless, it seems that an imagination cannot be replicated in the mind to the same extent as a stimulus driven system such as VWM. Indeed, sensory processes appear to be an essential aspect of VWM capacity. Comparing VWM and imagery capacities indicates that visual input appears to support ~ 25% of VWM capacity. To date, this is the first time that the contribution of sensory input to VWM capacity has been estimated, and it highlights the importance of sensory information for cognitive processes. Therefore, future research should consider the initial input of information when assessing the capacity of processes.

An alternative explanation for the capacity differences between imagination and VWM could be that imagining similar stimuli creates more interference. This interpretation is tentatively suggested because the evidence only comes from secondary analysis (i.e., colour repetition analysis) from Experiment 6. Here it was found that colour repetition harmed imagination performance in comparison to VWM. It could therefore be that imagining only black blocks as in Experiment 1 – 5, systematically harmed imagination relative to VWM. However, no firm conclusions can be drawn here as this interpretation is only based on secondary analysis. Future research should therefore explore the effect of stimuli similarity on imagination capacity.

Throughout the thesis, self-reported vividness was assessed on each trial in order to compare with data on performance. Performance data was assumed to reflect the operations of the internal processes the experiments were designed to interrogate (imagery and short-term visual memory) and so comparing against self-reported vividness offered a sense check of this assumption. The relationship between performance and vividness has been fairly consistent throughout this thesis, with imagery performance and vividness both being lower than that of visual memory (Experiments 2 – 5). Therefore, it seems highly likely that the above explanations could equally explain the vividness findings. One exception was the findings from Experiment 6, with vividness ratings being similar between imagery, VWM and VSTM, whereas performance was lower in imagery than VWM. This might just be a feature of using colour stimuli, but it is unclear why.

11.4 Implications

11.4.1 Theoretical implications

There is significant evidence that imagery is generated using top-down connections from fronto-parietal regions to areas such as the early visual cortex (Dijkstra et al., 2017; Mechelli et al., 2004; Pearson, 2019). It may be that during imagery, top-down connections activate regions of the early visual cortex, such as area V1 and V2 to fill in the visual detail of the representation. This interpretation is consistent with the *Reverse Hierarchical Model* proposed by Pearson (2019; also see Ahissar & Hochstein, 2004). The model put forward by Pearson (2019) suggests that imagery involves an interconnected network that spans from the frontal cortex to the occipital regions, which works in reverse order to that of perceptually driven images. In summary, the frontal cortex is said to be where the process of generating an image begins. The second stage involves activation of the medial temporal lobe, which is associated with memory encoding or and information and memory storage. Finally, the model posits that neural activation propagate to the early visual cortex, and also the parietal cortex if the representation has spatial properties (for review of the Pearson model see section 2.1.2). The data appear consistent with this conceptualisation, because the lower capacity in imagery can be explained by less precise activation in lower-level sensory areas by top-down generated activation.

This research was primarily focused on the relation between imagery and VWM capacity rather than investigating subsystems of imagery (Kosslyn et al., 1994, 1997, 2006) and VWM (Multi-component Models, e.g., Baddeley & Hitch, 1974; Hitch et al., 2020; Logie, 1995, 2003, 2011). Although, the work here does not specifically test proposed systems of imagery and VWM, the capacity differences found between imagination and VWM support the idea that separate systems may be used (Logie 1995, 2003, 2011; Logie & van der Meulen 2009; Pearson 2001; Quinn & McConnell, 2006).

Interestingly, there is little focus in VWM theories on the importance of bottom-up visual input during the initial and subsequent aspects of processing (e.g., Baddeley & Hitch, 1974; Baddeley, 2000; Barrouillet et al., 2004; Cowan, 2016). Most VWM theories mention the role of sensory input (e.g., incoming information can be held in the focus of attention over a period of time; Cowan et al., 2020), but do not explain the *importance* of bottom-up visual input. For example, Cowan et al. (2020) describes his *Embedded Process Model* by noting that "the first component is a brief sensory store that persists for a few hundred milliseconds after presentation of a stimulus as it registered in the brain and is experienced as continuing sensation even if the actual stimulus has abruptly ceased" (pp. 44). However, Cowan et al. (2020) do not explain if this sensory store is activated in the absence of incoming sensory input. Even though, neuroscience studies on imagery and VWM support this (e.g., Albers et al., 2013). The findings in this thesis support the idea that imagery and VWM are very similar, but are not identical, with the difference being that sensory input may account for the increase in capacity for VWM relative to imagination. As such, VWM theories should give further consideration to the importance of bottom-up sensory information in models of working memory.

Finally, the current research does not provide evidence as to whether an image is pictorial in nature (Kosslyn et al., 1994, 1997, 2006) or propositional (Pylyshyn, 1973, 1981, 2002, 2003). However, there is significant support neuroscience and behavioural evidence that supports the pictorial account of imagery (e.g., Albers et al., 2013; see Pearson & Kosslyn, 2015 for discussion).

11.4.2 General implications

The data here show differences between a more passive and simultaneous presentation task (VSTM) and a more active manipulation task (VWM). One of the key differences being the use of relational information in the VSTM task, but not the VWM task. This has significant implications when interpreting capacity estimates in short-term visual memory tasks. For example, capacity estimates from any simultaneous task are probably overestimates, unless those tasks had ways of preventing relational information being used (such as in Experiment 6).

Throughout this thesis, performance in the VWM and imagery tasks were more similar and varied together and correlated more strongly than either the imagination and VSTM tasks or the VWM and VSTM tasks. This shows that imagination and VWM are share more similar underlying processes than between VWM and VSTM. This seems surprising given that the imagery task had no sensory input. The VSTM task relied on relational processing and did not involve any of the manipulation. Experiment 5 seems to show that when doing sequential build up, presenting relational information at test actually harms performance. This suggests that VSTM and VWM tasks seem to utilise very different systems that are not comparable. Interestingly, the lack of sensory input in imagination did not render that task less related to VWM than VSTM. This further underlines the idea that imagery and VWM rely on more similar cognitive processes than that of VWM and VSTM. Furthermore, these interpretations highlight the need to move away from the idea of ‘name tags’ for cognitive constructs or tasks and rather explore the underlying processes that are involved in each task. This is further supported by the stronger correlations found between imagination capacity and Corsi span. The Forward and Backward Corsi tasks are viewed as a measure of visual working memory capacity (e.g., Vandierendonck et al., 2004). However, this ‘VWM’ measure is not a pure measure of VWM as it taps into multiple resources/processes (Donolato et al., 2017). The findings here rather suggest that the Corsi tasks should not be used as a measure of VWM capacity because of the corelation data and overestimates of capacity (~6). Again, this shows that caution should be used when suing ‘name tags’ and rather a focus should be on the underlying processes that terms refer to or that are involved in different tasks.

The correlations in the individual differences chapter suggests that established vividness measures (i.e., VVIQ and VOSI) are very poor indicators of *performance*, with these measures showing no correlation with performance. It could be that vividness tends to focus on the experiential side of imagery rather than the structural/spatial aspect. As a result, you can have a mental representation of structure (e.g., an array) without experiencing vivid imagery and you can have vivid imagery without underlying structure (e.g., from autobiographical memory).

Strengths, limitations and future directions

One of the main strengths of this thesis is the development of a novel paradigm that enables capacity to be measured using comparable tasks for imagination, VWM and VSTM. The only notable difference between the three tasks was the way in which information was presented to participants during build-up. In the imagination task, arrow cues were used to cue participants to imagine objects at a specific location. In contrast, during the visual memory tasks, participants were presented with objects at location. To date, this paradigm provides one of the cleanest and most direct methods for measuring capacity of, and comparing capacity between, imagination and VMst. However, given that this study uses a specific instantiation of a visual paradigm, future research should investigate the capacity of imagination and visual memory using other task operationalisations to see if the capacity findings replicate.

While the findings are based on relatively homogenous samples of UK undergraduates (mostly female), it is expected that the mechanism underlying imagination to generalise to other healthy adults which could be confirmed with replications across cultures. However, it would be interesting to investigate if the capacity findings can be replicated in healthy older adults. Older adults generally have larger sensory deficits relative to younger adults, and many age deficits in cognition can be statistically explained by older adults' deficits in hearing and sight. For example, older adults typically have psychophysical deficits in visual function compared to younger adults (see Li & Lindenberger, 2002; Owsley, 2010, for reviews). In line with this framework, if visual working memory is enhanced by utilising visual input, then such an enhancement may be smaller in older adults because their senses have declined. Therefore, the difference between VWM and imagination capacity might be smaller for older adults than for young adults. It would be particularly interesting if older adults showed no imagination deficit relative to young adults.

Throughout the thesis only relatively simple objects were used (e.g., coloured blocks) to investigate imagination and visual memory. It would be interesting to see if making the objects more complex (e.g., binding shape, colour and location) affects capacity. Additionally, using real-world objects could improve imagination and VWM capacity. Indeed, Brady et al. (2016) found an increase in VWM capacity when participants were presented with real world object relative to simple stimuli (although see Li et al., 2020). It is thought that this increase is due to activations of episodic visual long-term memory (Cowan, 2001; Lin & Luck, 2012). It would be interesting to see if generating and maintaining real world objects could boost imagination capacity more than when using simple stimuli.

There is much debate in the literature as to how capacity limitations arise in visual memory (for review, see Oberauer et al., 2016). Two of the main theories to account for the capacity of VWM are slot-based models (e.g., Awh et al., 2007; Cowan, 2001; Luck & Vogel, 1997) and resource-based models (e.g., Alvarez & Cavanagh, 2004; Bays & Husain, 2008; Franconeri et al., 2013; Wilken & Ma, 2004; see van den Berg et al., 2014 for comparison between models). The purpose of the work reported here was to directly compare modelled capacity estimates for imagination and different short-term visual memory tasks. Whilst the modelling approach utilised here fit a paradigm that focused on the number of objects represented, no claims are made with regard to whether capacity limitations are due to the number of slots or due to a general limited capacity resource. Rather, the findings simply indicate that imagery has a lower capacity in comparison to VWM. Future research should aim to explore slot-based and resource-based models in imagination and compare this with short-term visual memory.

11.5 Original contribution of the current research

Substantial literature has established capacity estimates for VMst. However, there was no evidence as to whether visual imagery has its own capacity limitations, and whether capacity of visual imagery is the same or different to that of VMst. A novel paradigm was developed in order to provide one of the cleanest and most direct measures of capacity for imagination and to be able to directly compare this with capacity in VMst. This paradigm was thoroughly examined by exploring the impact of presentation time, placement of cues, grid size, number of locations and decision at test on performance. The findings of these explorations provides a solid basis for other researchers to use this paradigm to measure capacity of imagination and visual memory in the short-term.

This thesis has provided original knowledge about the relation of imagination capacity and performance relative to different short-term memory tasks that draw on different processes. Overall, the evidence provided in this thesis suggest that imagery and VWM are highly related processes, whereas imagery and VSTM are underpinned by different processes and mechanisms. Additionally, the evidence suggests that VWM and VSTM share fewer cognitive processes than imagination and VWM.

Previous research often uses the terms VWM and VSTM interchangeably, and in some instances, the term imagination is used to describe visual memory. This lack of clarity suggests that these terms are used without due consideration of the processes underlying these terms or the tasks associated with these terms. This thesis provides strong evidence for researchers to move away from the idea of ‘name tags’ and investigate the underlying processes in these different terms. For example, researchers should explain how and why they are using a specific term (e.g., VWM instead of VSTM) as this will enable researchers to better understand the underlying processes in memory and improve scientific discourse.

Understanding imagery capacity has some important implications as imagery is seen as essential for navigating and predicting our environment and is involved decision making and emotion regulation. The experiments conducted explored the capacity of imagination and visual memory in the short-term using comparable tasks. An original contribution to knowledge was made by estimating imagery capacity for the first time and finding that the capacity of imagination is lower than that of VWM. In addition, the importance of initial sensory input in supporting VWM has been estimated for the first time, with visual input appearing to support ~25% of VWM capacity. The findings provide insight into the processes and mechanisms involved in imagination and visual memory in the short-term.

11.6 Conclusion

Overall, the findings suggest that imagination and VWM are highly related, with the caveat being that imagination capacity is lower than that of VWM. This lower capacity could be due to one, or a number of the following reasons: the lack of sensory input, the use of different sub systems and the reliance on top-down processes to generate and maintain an imagination. Einstein is reported as saying “Logic will get you from A to B. Imagination will take you everywhere”. The data suggest that imagination might not take you much further than imagining A and B.

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