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ESTIMATING THE CAPACITY OF VISUAL SHORT-TERM MEMORY:
A TRANSCRANIAL DOPPLER SONOGRAPHY STUDY

by

Natasha Barrett

Under the Direction of David A. Washburn

Abstract

Estimates of the capacity of visuospatial short-term memory (VSTM) have ranged from less than 1 item to 4 +/- 1 items. The purpose of the present study was to find the capacity of VSTM by looking at the contribution of the other working memory systems (phonological loop and central executive) and determine the factor that limits VSTM capacity (either number of objects or object complexity). In this study, the psychophysiological measure of cerebral blood flow velocity also was incorporated to determine whether changes in cerebral blood flow velocity were indicative of VSTM performance and capacity. Both performance measures and cerebral blood flow velocity indicate that capacity for random polygons is approximately one object. Complexity of the objects affected capacity, such that simple objects had higher capacities and lower cerebral blood flow velocity than complex objects. Other working memory systems were not found to have an effect on performance.

INDEX WORDS: Visuospatial memory, short-term memory, hemovelocity, transcranial Doppler (TCD), capacity

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by

Natasha Barrett

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Master of Arts

in the College of Arts and Sciences

Georgia State University

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Natasha Barrett
2007

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Introduction

The Capacity of Memory: Behavioral Estimates

It has been more than 50 years since “the magical number 7, plus or minus 2” (Miller, 1956) defined the limits of information processing and helped to usher in a new era of cognitive research in psychology. Five decades later, memory theorists have largely abandoned this elegant generalization in favor of more complex answers to the question, “How much information can be retained (or otherwise processed) for brief periods of time?” Researchers have suggested that this answer is complicated by the nature of the information to be remembered, by the type of test or measure used for assessment, and of course by the length of time that the information must be retained. For example, Cowan (2001) argued that the capacity estimate of 7 +/- 2 items is an overestimation. He reviewed findings showing that when the ability to chunk (or combine) items is controlled, the actual values of short-term storage capacity fall closer to 4 +/- 1 items. Cowan theorized that this capacity limitation is due to a general limitation in the focus of attention.

However, other researches have contended that even this generalization is too broad. One of the most influential current theories of memory is the working memory model proposed by Alan Baddeley and colleagues (e.g., Baddeley & Hitch, 1974; Baddeley, 1986, 1999, 2002). In this model, the capacity of working memory varies as a function of the type of information to be remembered, because each type of information is stored in its own modality-specific buffer. This suggestion is fundamental to the present study; therefore, it merits further discussion. Subsequently, I will discuss the implications of this model for the assessment of memory capacity—or more specifically,

the capacity of short-duration memory for visual and nonverbal information. Studies will be reviewed that show the need to control other cognitive processes that may contribute to recognition, and thus that may contribute variability and inflation to estimates of memory capacity. Finally, I will contrast two theoretical frameworks with respect to working memory capacity, where these rival frameworks make opposite predictions about the effects of stimulus complexity on memory capacity.

Baddeley's model of working memory. According to Baddeley and colleagues (e.g., Baddeley & Hitch, 1974; Baddeley, 1986, 1999, 2002) working memory is a multi-component construct in which a central executive unit coordinates information that is stored in several content-specific slave storage (memory) systems. In Baddeley's original formulation of the working memory model, there were two slave storage units: the visuospatial sketchpad and the phonological loop (e.g., Baddeley, 1986). In recent writings, Baddeley (2002) has described a third slave system (the episodic buffer), and conceivably there could be many others yet to be described. Further, Baddeley (2002) theorized that the visuospatial sketchpad was responsible for both visual information and spatial information; however, other research indicates that these two types of information may be further dissociated into their own separate subsystems within the visuospatial sketchpad (Logie, 1995; Neath & Surprenant, 2003).

Irrespective of the actual number of slave systems, the central executive component of the working memory system includes those processes responsible for reasoning, decision making, coordinating the slave systems, and focusing attention (Logie, 1995). The slave storage system that has generated the most research is the phonological loop, which refers to the processes by which verbal, acoustic, or articulatory

material is stored and rehearsed over short terms (seconds to minutes). The distinction between the phonological loop and the visuospatial sketchpad was made on the basis of a series of empirical dissociations that have been reviewed and debated elsewhere (e.g., Baddeley, 1986). For the present study, it is important only to note that the characteristics of phonological working memory are different from the parameters of visuospatial working memory, with respect to the type of information stored, the types of concurrent tasks that interfere, the duration of storage, the mechanism of rehearsal, and the amount of information that can be stored.

The visuospatial sketchpad, either as a general construct or a collection of modality-specific sub-buffers, includes the cognitive processes required to store visual and/or spatial information from the environment for short periods. It has been suggested that there may be an “inner scribe” or spatial mechanism for visuospatial rehearsal (Logie, 1995) as an analog to the “inner voice” that supports verbal rehearsal; however, others have failed to yield evidence for rehearsal in the visuospatial sketchpad (Washburn & Astur, 1998). In either case, if the visuospatial sketchpad is the same cognitive system that Kosslyn (1981) called “the spatial medium” for imagery, then it is clear that information decays in the visuospatial sketchpad unless refreshed in some way (either rehearsed or retrieved afresh from long-term memory).

Capacity is the maximum number of objects or items that can be retained, and is usually estimated by the number of stimuli that can be correctly recalled or recognized (Logie, 1995). Studies of the capacity of the phonological loop reveal a time-based limit, such that about 2 seconds worth of phonological information can generally be retained accurately (Baddeley, Thomson & Buchanan, 1975). In contrast, the visuospatial

sketchpad—which has been studied much less extensively than has the phonological loop—has yet to yield a consensus capacity estimate. The present research is designed to resolve this ambiguity.

Visuospatial Sketchpad or VSTM? The suggestion that the capacity of working memory for phonological information may be different from the capacity of working memory for visuospatial memory is fundamental to the present study. That said, the present research is not wed to Baddeley's particular working memory model. Theorists such as Cowan (1995; 2001) who oppose the notion of separate memory stores may nonetheless acknowledge that the amount of verbal information that can be remembered may differ from the amount of visual or spatial information that can be retained. Whereas Baddeley's terminology provides a useful framework for describing the cognitive constructs that support working memory, I will use the more general term "visual short-term memory" (VSTM) to describe the retention of visual information, whether or not that information gets buffered in a way that could be considered a visuospatial sketchpad.

VSTM allows an individual to retain visual and/or spatial information from the environment for a few seconds (Logie, 1995), and it is severely limited in capacity (Luck & Vogel, 1997). As was suggested above, previous research provides a range of estimates with respect to the actual capacity of VSTM. For example, Vogel, Woodman, and Luck (2001) found a capacity of 4 +/- 1 items, similar to the limit proposed by Cowan (2001). However, Phillips and Christie (1977) presented participants with checkerboard or matrix stimuli and then tested memory with a completion task. They observed that performance was particularly good only for the last image presented, and concluded that VSTM was limited to one item. Similarly, participants have also been

shown to recall no more than one pseudo-random form (Barrett & Washburn, 2006a,b; Barrett, Washburn, James & Gullledge, 2005) when the pseudo-random forms resembled a child's scribble. In these studies, observers were required to focus on the presentation and then to draw the forms on paper. In this procedure, recall capacity averaged around one-third of an object.

The purpose for the present study was to reveal the capacity of visual short-term memory and determine the variables that may have produced variability in previous estimates of VSTM capacity. In order to find the capacity of VSTM, any contribution of the phonological loop and the central executive must be determined.

Contributions of Other Cognitive Processes to VSTM

Cowan (2001) proposed that to measure pure capacity limits, one must remove the ability to utilize processes that artificially increase capacity. Disagreement among estimates of the capacity of VSTM may arise when memory systems other than VSTM are contributing to performance. For example, one might retain more visual information if those images can be named and rehearsed phonologically. Alternatively, the central executive may allocate additional attention to that information in some tests compared to others. Therefore, these other components need to be controlled or limited to get a pure measure of the capacity of VSTM as a unique and independent system. According to Cowan, there are three methods for accomplishing this: 1) using information overload that blocks the ability to chunk, 2) blocking the recoding of the stimuli, and 3) analyzing the data for performance discontinuities or analyzing the indirect effects of the capacity limitation. These methods can be used individually or in conjunction with one another.

Phonological Memory. Conflicting evidence exists as to whether the phonological-memory processes actually contribute at all to VSTM¹. On the one hand, the visuospatial sketchpad and the phonological loop may indeed be separate systems, but they work together and overlap in visuospatial situations with semantic meaning or auditory situations with nonsemantic details (Sharps & Pollitt, 1998). Several researchers have shown that VSTM performance is improved when verbal memory is available to help with retention (Paivio, 1990; Postle, D'Esposito & Corkin, 2005; Silverberg & Buchanan, 2005). Conversely, others have found that VSTM capacity is unaffected by manipulations that occupy verbal memory systems (e.g., Phillips & Christie, 1977; Pashler, 1988; Vogel, Woodman & Luck, 2001; Morey & Cowan, 2004; 2005; Eng, Chem & Jiang, 2005). At a minimum, it seems clear that the phonological loop is not utilized consistently to support VSTM. It may be that object memory is affected more than spatial memory by removing contributions of the phonological loop. Therefore, in the present study, I focused on whether verbal memory contributes to visual-object memory in change-detection tasks.

Any contribution of verbal memory to VSTM can be removed through several different procedures. Briefly presenting stimuli reduces the ability to encode phonologically the stimuli (Frick, 1988). Use of stimuli that do not have simple verbal codes (e.g., irregular shapes or random polygons) would also reduce the use of verbal memory (Cermack, 1971). Matrix patterns also resist being verbal encoded (Phillips, 1974). Dual-task paradigms can also be utilized to remove the contribution of other mechanisms to working memory. Dual-task paradigms can remove the contributions of the phonological loop by engaging the mechanism in another task (e.g., maintaining a

concurrent verbal memory load). In the present study, I employed articulatory suppression to occupy the phonological loop. Articulatory suppression is the repetition of a sound or series of sounds such as the word “the” to engage the phonological loop so that it cannot be used to recode or to rehearse information (Baddeley, 1999).

Central Executive. Several researchers have stressed the need to control for contributions from the central executive (attention), as well as from the phonological loop, in estimating the capacity of VSTM. Backwards counting, concurrent verbal load and articulatory suppression remove the phonological loop, but only backwards counting and concurrent verbal load involves both the phonological loop to rehearse and also the central executive to focus attention (Morey & Cowan, 2005). Performance on a change-detection task was found to be impaired by backwards counting of one and three, and a concurrent load of 6 or 7 digits rehearsed aloud (Allen, Baddeley & Hitch, 2006; Morey & Cowan, 2004). Phillips and Christie (1977) studied the effects of different types of interference in VSTM by using block patterns formed using a matrix pattern in a change detection task. During the retention interval, the participant performed one of four conditions of interference. The interference condition of addition, whether verbally or visually, decreased performance in the visual task, but reading of the numbers did not decrease performance. Performance decreased because of active perception of the patterns in VSTM more than viewing the patterns without trying to encode it for a future test. Phillips and Christie (1977) concluded that cognitive tasks interfere with VSTM if performed during retention, and, as discussed previously, that VSTM is limited in capacity to a single, terminal item. Capacity also is reduced when the recognition test for the verbal load is performed during the retention interval of visual change-detection task

(Cocchini, Logie, Della Sala, MacPherson, & Baddeley, 2002). These findings support the theory that the central executive is utilized by the VSTM to increase task performance.

These studies indicate that the phonological loop is not the only mechanism that could be contributing to VSTM performance and thereby producing variability in estimates of VSTM capacity. VSTM is a product of attention, control processes, and visual memory (Fougnie & Marios, 2006). As such, tasks that utilize attention focusing and controlling by the central executive do interfere with VSTM capacity (Cocchini et al., 2002; Morey & Cowan, 2004; 2005; Allen et al., 2006). However, the previous research focused on spatial memory exclusively; dissociation of the contributions from the central executive and phonological loop to VSTM was achieved only for spatial memory and not object memory. Consequently, the current study was focused on object memory to determine whether concurrent central executive tasks adversely affected performance. Following Morey and Cowan (2004; 2005), I used a concurrent verbal memory load to absorb attentional resources from the central executive.

What is the limiting factor of Capacity of VSTM?

Two different theories have been proposed that explain the capacity limits of VSTM. The object-based theory states that the capacity of VSTM is established by the number of slots available, such that VSTM can hold a limited number of objects (believed to be about 4), but that each object can have any number of features (Vogel et al., 2001). According to the object-based representation model, one parameter limits VSTM: the number of objects that are stored. Vogel and colleagues (2001), discussed above, presented participants with a change-detection task. The stimuli within the

displays were colored squares that varied in the different features (i.e. orientation, location, and texture).

A rival theory suggests that VSTM does not have fixed number of slots for objects, but rather that VSTM has flexible resources to hold information (Alvarez & Cavanagh, 2004; Song & Jiang, 2006; Xu & Chun, 2006). In the flexible resource model, VSTM capacity has a limited amount of resources to divide between objects. As the complexity of each retained object increases, more resources are utilized, such that fewer stimuli can be retained. For example, Alvarez and Cavanagh (2004) used a change-detection paradigm to test the flexible resource theory by presenting six stimulus types: colors, letters, Chinese characters, random polygons, shaded cubes and Snodgrass drawings (Snodgrass & Vanderwart, 1980). The complexity of the stimulus was determined by measuring the processing rate in a visual search task. The capacity of VSTM varied for each stimulus type. This finding was replicated with longer presentation durations (Eng et al., 2005), and colors have a significantly higher storage capacity than shapes (Allen et al., 2006). Objects with multiple features have significantly lower VSTM recognition capacities than objects with only one feature dimension (Wheeler & Treisman, 2002; Xu, 2002). Capacity was found to be 3 objects in the color only condition and 2 objects in the shape only condition (Song & Jiang, 2006).

One problem however is that the definition of complexity has varied widely across previous studies. The complexity of the stimuli used in these studies has ranged from simple colors (Vogel et al., 2001) to complex faces (Eng et al., 2005). Thus, the range of capacity estimates across studies may reflect the differences in the definitions of

object complexity. Complexity has been defined as information load attained through visual search rate (Alvarez & Cavanagh, 2004; Eng et al., 2005) but visual search rate can be affected by a multitude of different factors and may not be indicative of complexity. Complexity of a stimulus also was operationally defined as the size of the matrix and how many blocks had dots in the matrix pattern (Phillips, 1974; Phillips & Christie, 1977). Reaction time in the change detection response increased as the matrix size increased (Phillips, 1974). However, this definition of complexity does not test the capacity limit of objects in VSTM, instead testing spatial memory. Matrix patterns filled in with color or dots tests the spatial abilities in the visuospatial sketchpad because the task requires determination of “where” the matrix was filled (Klauer & Zhao, 2004). Complexity has been defined as the shape features of a stimulus (Xu & Chun, 2006) or the number of features that object has (Song & Jiang, 2006). Yet, this definition does not separate the affects of binding from complexity. The varying definitions of complexity may be the reason why the research in complexity has not found more support for the flexible resource model, as each definition has potential flaws.

The present study will test whether VSTM capacity is influenced by object complexity. To avoid the previously discussed problems behind different definitions of complexity, the current study incorporated Attneave polygons (1957), where complexity could be defined as the number of turns (points or angles or sides) in the object. For the present study, performance was compared between simple and complex stimuli.

The Capacity of VSTM: Psychophysiological Estimates

Neuroimaging Research. There is reason to believe that measures of brain activity could inform the study of VSTM capacity. Prior research using functional

magnetic resonance imaging (fMRI) gives support to the differences that exist due to the workload of the items and the task. fMRI studies can indicate very specific regions that are active during cognitive tests.

Activation in the intraparietal and intraoccipital sulci (IPS and IOS, respectively) increased with memory load (the number of objects encoded; Todd & Marois, 2004). This finding generalized across stimulus types of colored disks and white bars of varied orientations. Perceptual load of a visual scene does not initiate activation of the IPS and IOS. Posterior parietal cortex activity predicted individual differences in VSTM capacity (Todd & Marois, 2005). Memory load affected multiple different areas of the brain during a change detection task. These areas affected were superior parietal lobule, presupplementary motor area, and inferior frontal sulcus (Song & Jiang, 2006).

Interestingly, researchers have incorporated the fMRI technique to test the effects of complexity on VSTM capacity. The activation in the superior intraparietal sulcus and the lateral occipital complex tracked the behavioral data showing differences in performance and activation increasing with number of objects shown when the objects were simple (Xu & Chun, 2006). The authors defined complexity as whether a shape was solid (simple) or various shaped holes (complex). When the objects were complex, capacity did not increase above two items. Activation in the superior intraparietal sulcus and the lateral occipital complex did not increase above the level of activation at capacity. Activity in the IPS and lateral occipital complex brain regions increases with the number of items presented, up to the capacity limit where activity asymptotes (Xu & Chun, 2006). The authors concluded that VSTM capacity is limited by both a fixed number of objects and by object complexity. Activation also varied due to the object's

complexity in the superior parietal lobule, where complexity was defined as the number of features of the object (color and shape; Song & Jiang, 2006).

Transcranial Doppler Sonography. A new technology exists that may help determine limits in VSTM. Researchers have used functional Transcranial Doppler (fTCD) sonography to investigate cerebral blood flow velocity (CBFV) in a number of visual tasks; however, no one has used fTCD to examine VSTM capacity. Researchers incorporated other neuroimaging techniques, namely fMRI, to investigate VSTM in the past, and the previously discussed results provide a basis for generating hypotheses about how VSTM tasks affects cerebral blood flow velocity, thus brain activation. The fMRI research suggests that CBFV would vary in the same manner.

The main advantage of using fTCD in the current study is that fTCD enables the manipulation of the change detection to see the relationship between those manipulations and the changes in cerebral blood flow velocity. CBFV shows brain activity as a function of the elements of the task (Duschek & Schandry, 2003). The ability of CBFV to measure the amount of workload that is generated by a task will allow brain activation to indicate which task requires more effort. For example, if complex objects are more effortful to recognize than simple objects, then CBFV will be higher for complex objects than simple objects. The larger the workload, the higher the CBFV will be in the brain.

fTCD sonography is a noninvasive procedure that uses ultrasound technology to continuously measure cerebral blood flow velocity through main stem intracranial arteries in the brain (Aaslid, Markwalder & Nornes, 1982). The three major arteries that can be measured are the middle cerebral artery (MCA), posterior cerebral artery (PCA) and the anterior cerebral artery (ACA) which are shown in Figure 1.

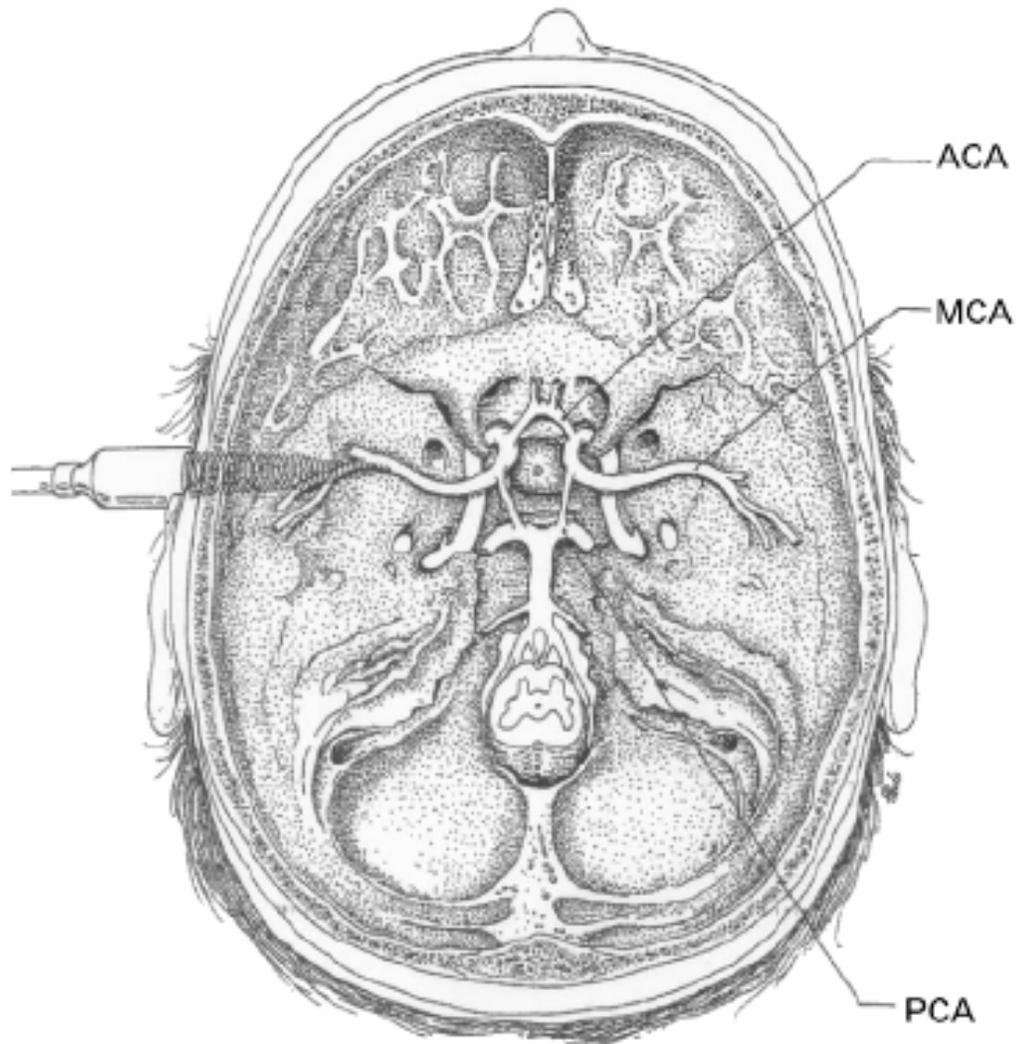


Figure 1: Location of basal cerebral arteries

Displayed is picture showing the location of the anterior cerebral artery (ACA), middle (medial) cerebral artery (MCA), and posterior cerebral artery (PCA). (Modified from Stroobant & Vingerhoets, 2000)

Transducers (ultrasound probes) send a Doppler ultrasound signal through the transtemporal window of the skull to the specified artery and receive that signal, thus the transducers work as both the source and receiver. Doppler sonography is a frequency shift caused by the movement between the source and receiver (Duschek & Schandry,

2003). In the arteries, erythrocytes (red blood cells) in the blood cause the frequency shifts picked up by the ultrasound signal. The velocity of cerebral blood flow is proportional to the size of the frequency shift. The transtemporal window is one of three areas in the skull that are thin enough to allow the ultrasound signal to penetrate the bone. Each artery displays different average velocities and directional flow, which allows for verification of the artery. The artery that was the focus of this study was the MCA as it supplies blood to the anterior, middle and posterior temporal arteries, the anterior and posterior parietal arteries, lateral orbitofrontal and ascending frontal arteries (Netter, 1989), and thus perfuses to approximately 80% of the brain. Figure 2 displays the perfusion area of the cerebral arteries.

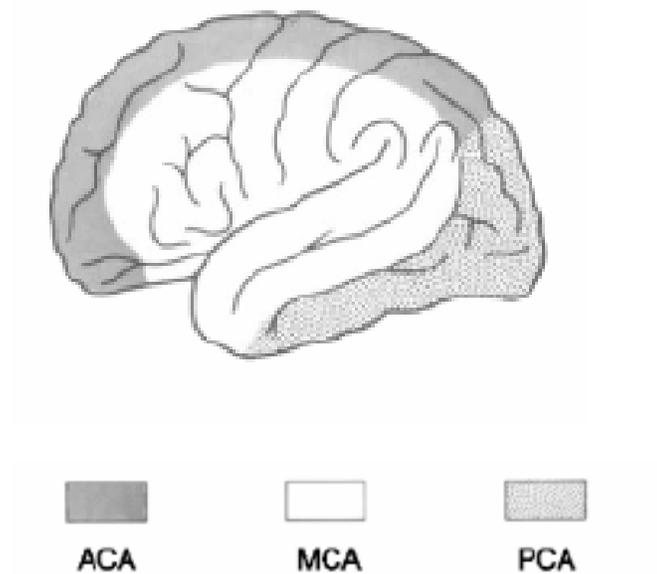


Figure 2: Perfusion regions of basal cerebral arteries

(modified from Angevine & Cotman, 1981).

Large basal arteries, such as the MCA, change their cerebral blood flow velocities as an effect of the demand in the brain regions that are serviced (Duschek and Schandry, 2003). Changes in cerebral activation and metabolism initiate changes in the cerebral blood flow velocity (CBFV). As the cerebral activation increases, the brain area engaged requires larger amounts of oxygen, removal of waste and local increase in $p\text{CO}_2$ (Stroobant & Vingerhoets, 2000). Therefore, as the workload increases in brain regions, CBFV to those regions increases. For example, visual and verbal tasks significantly increase CBFV from baseline conditions (Bulla-Hellwig, Vollmer, Gotzen, Skreczek, & Hartje, 1996; Cupini et al., 1996; Silvestrini, Cupini, Matteis, Troisi, & Caltagirone, 1994).

fTCD has distinct advantages in its use. fTCD has excellent temporal resolution, showing CBFV changes from visual stimulation as short as 34 milliseconds (Duschek and Schandry, 2003). Two transducers allow comparison between the lateralization of behavior in each hemisphere. Recordings of CBFV also have the advantage of being continuous throughout the task. The biggest advantage of fTCD is in the practical uses. It is more cost effective than fMRI and allows the participant to move more freely since a helmet holds the transducers in position to enable movement. Application of the fTCD and use during testing causes much less stress on participants than fMRI.

The benefit of fMRI is that of high spatial resolution, but the fTCD has high temporal resolution and allows psychophysiological research paradigms to resemble those used in the research that looks at only the behavioral data. With the differences between fMRI and fTCD, one assumption must be met: the activated brain regions must coincide with the perfusion territory of MCA. The MCA perfuses most of the lateral

surface of the brain (Angevine & Cotman, 1981), thus covering the lateral part of the frontal, parietal, temporal and occipital cortices of the brain (Hanaway, Woolsey, Gado, & Roberts, 1998). The more specific parts of the brain fed by the MCA are: lateral portions of orbital gyri, large parts of precentral and postcentral gyri, superior and inferior parietal lobules, superior and middle temporal gyri temporal pole, motor and premotor areas. The MCA also extends caudally to supply most of lateral gyri of the occipital lobe. The intraparietal sulcus divided the portions of parietal lobe caudal to postcentral gyrus into superior and inferior parietal lobules (Carpenter, 1976). All the active brain regions found in fMRI research of VSTM are regions where blood is profused by the MCA.

The benefits that exist in the use of this technology make it considerably useful in the current study. CBFV will vary as a function of the task performed and as a function of the difficulty of the task. As stated previously, this measure will determine if differences in CBFV exist caused by the number of objects presented during a change detection task. CBFV would also indicate differences caused by the workload of the items; thus, if the brain has more activation when shown simple versus complex objects.

In addition to the utility of fTCD as a measure of differences in brain activation, fTCD also would show whether any lateralization that exists due to using the visuospatial sketchpad. Research that has used fTCD to measure CBFV has focused on hemispheric differences in verbal and visual tasks. However, fTCD has not been used with change detection tasks to determine the changes in CBFV while manipulating variables related to working memory capacity. Use of fTCD with a change detection task would determine whether a hemispheric lateralization existed for the task.

The verbal-spatial model suggests that the left hemisphere is dominant in linguistic tasks whereas the right hemisphere is dominant for nonlinguistic or visuospatial tasks (Milner, 1971). Although the findings are not perfect, research that included fTCD does indicate support for the verbal-spatial model. Various verbal tasks were found to have the left hemisphere dominant in terms of its CBFV (Bulla-Hellwig et al., 1996; Silvestrini et al., 1994). Visuospatial tasks increased CBFV in the right hemisphere significantly more than the left hemisphere (Bulla-Hellwig et al., 1996; Cupini et al., 1996; Silvestrini et al., 1994). According to the verbal-spatial theory, left lateralization would show support for object memory using the verbal abilities, whereas right lateralization would show support for object memory being a task that focusing on visual and spatial abilities.

Hypotheses

Capacity estimates of VSTM have varied widely across the research. The present study was designed to determine whether differences in stimulus complexity and control conditions were responsible for the variance in published capacity estimates. Interference tasks and object complexity were manipulated to determine which factors explain the variance in performance.

I hypothesized that removal of the ability to use the phonological loop through articulatory suppression would not affect performance, whereas removing the ability to use the central executive through a concurrent verbal load would decrease performance. I also hypothesized that capacity would vary according to stimulus complexity, as predicted by the flexible resource theory. I anticipated that as memory load increased, accuracy would decrease. That is, I anticipated that capacity would be less than 4 items.

Finally, I expected that these effects would be evident from the CBFV measure as well as from performance. That is, I hypothesized that CBFV would increase with increases in stimulus complexity and, to an asymptotic level, with increases in memory load. That asymptote would correspond with capacity. If indeed the brain is more activated when processing simple versus complex objects, this will favor the flexible resource theory. If CBFV does not differ between levels of complexity, then the object-based theory would be supported.

I predicted that the right hemisphere would be more active for the change-detection task due to right lateralization for visual items that are not easily verbally encoded (Milner, 1971). However, the concurrent tasks that use verbal tasks (articulatory suppression task and concurrent verbal load task) should cause the left hemisphere to be more active due to language being predominantly a left-hemisphere function (Milner, 1971).

Method

Participants

Forty-two participants (32 females and 10 males) from the Georgia State University research participant pool participated in this study. Age ranged from 18 to 32 with a mean of approximately 20.6 years. Due to the experimental design of researching lateralization effects, only right-handed individuals were recruited to participate in the experiment. All participants were required to have normal or contact corrected-to-normal vision. Participants who wore glasses were excluded, as the frame of eyeglasses interfered with the ability to acquire a signal with the apparatus. Five participants were tested but were not included in data analyses due to a programming problem. One

participant was excluded due to failure to follow directions. Fourteen participants were not included in the analyses because a reliable and stable signal for fTCD (see below) could not be obtained. Thus, 22 volunteers were included in the analysis. The recruitment took place using Sona Systems. All participants received two research-credit hours for their participation, which took approximately two hours.

Only participants that presented a consistent CBFV signal from both hemispheres were included in data analyses. A consistent signal was determined by the waveform of the signal. If the waveform was the same from heartbeat to heartbeat, then it was stable and consistent. The participant had to be able to turn her or his head from side-to-side slowly without the signal disappearing or becoming unstable. If it was determined that a signal could not be obtained in both hemispheres, the participant was debriefed and allowed to leave. All participants received the full two credits whether or not the signal was obtained.

Apparatus and Procedure

Upon arrival, the participant completed a consent form and optional demographics form. The Edinburgh handedness inventory (Oldfield, 1971) then was completed to verify the right-handedness of the participant. The experimenter then verbally explained the apparatus being used and the directions for the task. After verifying that the participant had no questions, the experimenter proceeded with setting up the equipment to find hemovelocity. Hemovelocity is cerebral blood flow velocity (CBFV) averaged across a specified interval. Participants were tested individually with the experimenter present during all phases to verify the continual functioning of all equipment and continual comfort of the participants. After completion of the change

detection task, participants were debriefed and thanked for their participation. After verifying the participants had no further questions, they were dismissed.

Transcranial Doppler Sonography. The Companion III Transcranial Doppler (TCD) unit (Nicolet/EME, Madison, WI, USA) measured hemovelocity. WinTCD software recorded the mean hemovelocity in both hemispheres. The participant was fitted with a Welder fTCD headband that held two 2-MHz ultrasound transducers steady at the transtemporal window located at the temples, as seen in figure 3. A small amount of Aquasonic-100 ultrasound transmission gel was applied to the face of each transducer and to the skin at the transtemporal windows to enhance the transducer's signal reception.



Figure 3: Demonstration of the fit of a Welder TCD headband

The headband holds two 2-MHz ultrasound transducers steady at the transtemporal window located at the temples.

Hemovelocity was measured in the middle cerebral artery (MCA) in both hemispheres and was recorded at depths of 48 mm to 56 mm, which was measured as the

distance between transducer face and sample volume. The recording depth was adjusted by 2-mm increments to compensate for differences in the skull size of the participant. The MCA sends blood to the anterior, middle and posterior temporal arteries, the anterior and posterior parietal arteries, lateral orbitofrontal and ascending frontal arteries (Netter, 1989), and thus perfuses approximately 80% of the brain (Stroobant & Vingerhoets, 2000). Hemovelocity is measured in centimeter/second and is usually time-averaged across a specified time interval. Fast Fourier Transformation (FFT) analysis produces a visual display that presents the three aspects of the data: velocity is on the vertical axis, time is on the horizontal axis, and the signal intensity is displayed in the multiple colors. The line of the display follows the cardiac cycle and corresponds to the maximum velocity in each cardiac cycle. Experimenters used this visual display to verify the signal.

After securing the signal, the participant stared at the blank computer screen for two minutes during which blood flow velocity was recorded. The two minutes of recorded hemovelocity was the baseline of mean cerebral blood flow velocity (CBFV) for the participant. The participants were instructed to relax comfortably with no talking during the baseline recording.

Stimuli. To define complexity objectively, I used Attneave (1957) shapes as the stimuli. Attneave and Arnoult (1956) developed a rigorous method of designing random polygons that could be ecologically valid (possessing the same parameters as natural forms), yet be random and novel. The polygons had closed contours and angular shapes, according to Method 1 for generating the shapes. Furthermore, the randomly generated polygons afford little or no information easy to encode verbally. Attneave (1957) used randomly generated polygons to measure how the perceived judgment of complexity

varied according to the elements of the polygon. The number of turns in the shape accounted for a large amount of the variance (80%). The number of turns was the number of points or angles or sides in the object. For the present study, two types of stimuli were created: simple and complex stimuli. Simple stimuli included 6 turns, with examples in Figure 4, whereas complex stimuli were composed of 12 turns, with examples in Figure 5. Each type of object contained 15 exemplars. Memory capacity was tested as a function of the complexity of the object.



Figure 4: Sample simple stimuli.

Examples of the simple stimuli that were used in the experiment. A total of 15 different simple stimuli were developed.

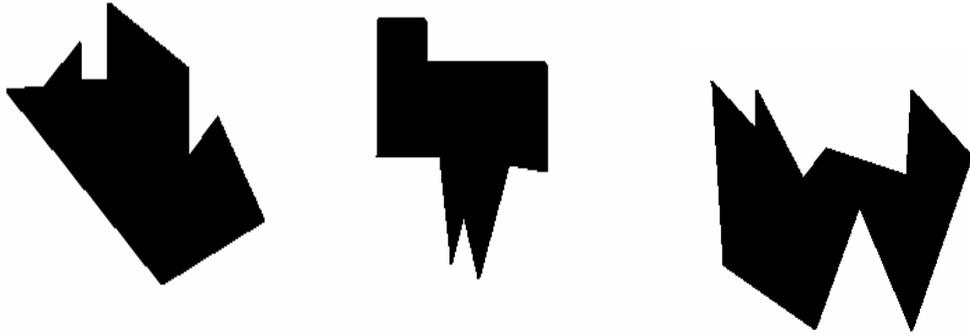


Figure 5: Sample complex stimuli.

Examples of the complex stimuli that were used in the experiment. A total of 15 complex stimuli were developed.

Procedure

Independent variables were stimulus complexity, memory load and concurrent task. Complexity referred to whether the stimuli were simple or complex polygons (as discussed above). Memory load was the number of objects presented in the target display and was 1, 2, or 3 stimuli. Concurrent tasks included an articulatory suppression task, a verbal load task, or no concurrent task (control). Each participant completed four blocks of trials. Each block consisted of the change-detection task performed with one concurrent task (or no concurrent task in the control condition). There were two control blocks, one to start the session and one to end the session. This enabled an analysis of the effect of familiarity and practice. Articulatory suppression and concurrent verbal load were randomly assigned to the second or third blocks respectively.

Each block contained 60 trials. Half of the trials included all complex stimuli and the other half included all simple stimuli. For each of the stimulus types (simple and complex), half of the trials involved a change in the array, and half of the trials involved

no change in the array. For each trial type, equal numbers of trials with 1, 2, or 3 stimuli were presented. Therefore, a total of 240 trials were completed by each participant, and each participant had the option to take a short rest between each block.

The experiment was presented on Dell computers using software written specifically for the experiment. Participants read instructions on the computer screen before each block of trials to inform them of the task requirements. Participants also were instructed to work as accurately and quickly as possible. During the dual-task blocks, described below, the participants were instructed to whisper quietly their responses as they rehearsed seven numbers, or repeated “the”. Normal vocalizations disturb the recordings of mean blood flow velocities because the voice frequency spectrum conducts via the head bones through the transducers (Stroobant & Vingerhoets, 2000; Diehl, Diehl, Sitzer, & Hennerici, 1990). Reading aloud in a whisper did not have artifacts in the CBFV recording (Diehl et al., 1990). Thus, the experimenter listened to the participant to confirm quiet rehearsal or articulatory suppression. If the participant forgot to rehearse quietly or rehearsed too loudly, the experimenter informed the participant and requested that the behavior be corrected.

Change detection task (Control Condition). The first block and last block of trials was the Control 1 and Control 2 conditions. The task was identical for both blocks. After reading the instructions, the participant pressed the spacebar to start the block. The participant looked at a fixation cross for 200 milliseconds, followed by the target display. The target display contained 1, 2, or 3 stimuli from one object type. The stimuli were presented within an invisible 3 x 3 matrix. The target display was presented for duration of 1,000 milliseconds. The target display was followed by a 2,000 milliseconds retention

interval of blank black screen. The test display contained one stimulus presented at the center of the screen. In half of the trials, the test stimulus was the same as one of the stimuli presented; in the other half of the trials, the test stimulus was changed. The participant was required to press the right mouse button if the stimulus was the same as one in the target display or the left mouse button if the test stimulus was changed (these buttons will be labeled accordingly). The test display was presented until the participant responded. Reaction times for responses and the responses themselves were recorded. Feedback on both of the responses was given as sounds. Correct trials resulted in a series of tones, whereas incorrect responses were followed by a buzzing sound. The intertrial interval was 2,000 milliseconds. A blank gray screen was shown between trials.

Articulatory suppression concurrent task procedure. Articulatory suppression was repetition of the word “the”. Repetition of “the” removes the ability to rehearse information in the phonological loop (Baddeley, 1986) but it does not require use of attention or verbal short-term memory. Articulatory suppression continued throughout the block of articulatory suppression. In the articulatory suppression block, the participant saw instructions on the screen that indicated that the participant should start quietly saying “the” aloud. After reading the instructions, the participant pressed the spacebar to start the block and started repeating “the” after pressing the spacebar. The change detection task was the same as the control condition procedure with the addition of repeating “the” throughout this block of trials.

Concurrent verbal load task procedure. The concurrent verbal load task was to rehearse and recognize a list of seven numbers. The concurrent verbal load of seven numbers was chosen because the paradigm used a recognition test instead of the recall

test that was used by Vogel et al. (2001). Concurrent verbal load also ensures that the phonological loop cannot rehearse visual information while the concurrent task of vocally rehearsing verbal items (series of numbers) engages the central executive (Baddeley, 1986; Morey & Cowan, 2004). Morey and Cowan (2005) theorized that rehearsing the digits aloud kept them in the focus of attention, which consistently engaged the central executive with the rehearsal of the digits. Silent rehearsal did not engage attention and the central executive because it did not keep the rehearsed items as the focus of attention. Thus, concurrent verbal load requires attention, verbal short-term storage, and the verbal rehearsal mechanism, whereas articulatory suppression only requires the rehearsal mechanism.

After the presentation of instructions, the participants pressed the spacebar to start the trials. A fixation cross was displayed in the center of the screen for 200 milliseconds. A verbal target display of a randomly chosen seven number sequence was displayed for 1,000 milliseconds. All seven numbers were displayed simultaneously at the center of the screen, which previously was occupied by the fixation cross. Participants quietly rehearsed the numbers until the verbal test display. A fixation cross was displayed for 200 milliseconds, followed by the visual target display that was displayed for 1,000 milliseconds. The target display was followed by a 2,000 milliseconds retention interval of blank black screen. The visual test display was presented until the response.

Following a response to the test stimulus, the participant was prompted to respond to the seven numbers of the test display. The participant was required to press the right mouse button if the stimulus was the same as one in the target display or the left mouse button if the test stimulus was changed (these buttons were labeled accordingly). This

verbal test engaged the phonological loop and the central executive. The intertrial interval was 2,000 milliseconds. A blank gray screen was shown between trials. Figure 6 presents a pictorial example of a concurrent verbal load trial.

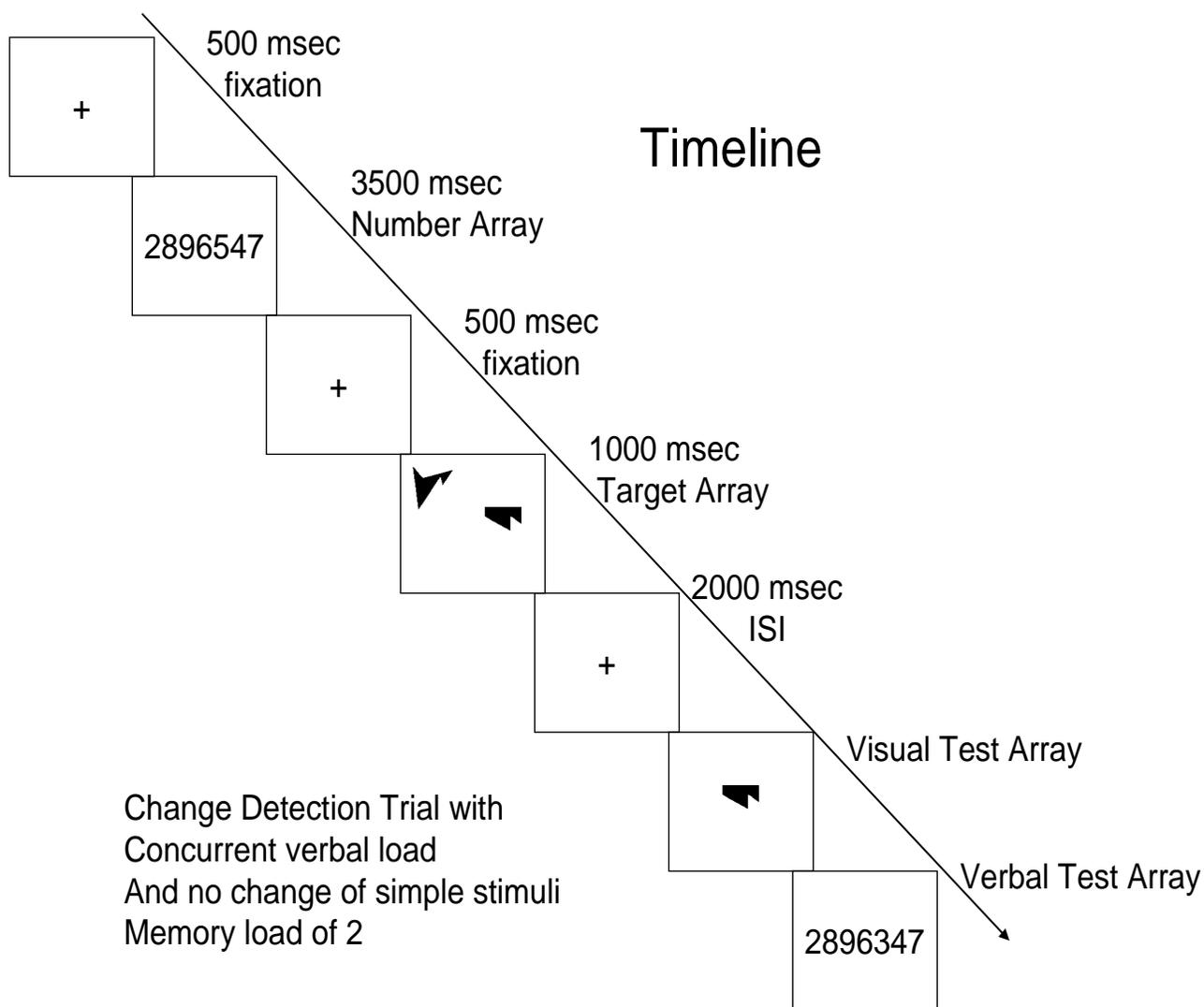


Figure 6: Concurrent verbal load timeline of experiment.

Example of the experiment timeline during the concurrent verbal load condition.

Results

Performance Data

To test for the effect of stimulus familiarity, performance was compared for the first block and the last block of trials. If familiarity of the stimuli affected performance then performance in the second block will be higher than the first block. If familiarity of the stimuli has no effect, no difference will exist between the two control conditions. Percentage correct was calculated for each participant. Performance in the first block (control 1) was compared to the last block (control 2). Control 1 was the first 60 trials performed and was in the control condition; thus, it did not contain a concurrent task. Control 2 was the last 60 trials and also was in the control condition. A paired-samples *t* test was conducted comparing percentage correct in control 1 to percentage correct in control 2. Performance did not differ between the two blocks, $t(21) = -1.807, p > .05$, indicating that familiarity of the stimuli did not affect performance. In all additional analyses of recognition accuracy, the control condition was collapsed across blocks.

A mixed-design 2 (order) x 3 (condition = control, articulatory suppression, verbal load) x 2 (stimulus type = simple or complex) x 3 (memory load = 1, 2 or 3) analysis of variance (ANOVA) with the percentage correct as the dependent variable was conducted. The variable of order was the only between-subjects independent variable; all other variables were within-subject variables. Order varied at 2 levels: in Order 1 participants received the articulatory suppression condition after control 1, then verbal load condition, followed by control 2; for Order 2 participants received verbal load condition after control 1, then articulatory suppression condition followed by control 2. Performance was significantly higher on trials with simple stimuli (79% correct, SE =

2%) than with complex stimuli (76% correct, SE = 1.8%), $F(1, 20) = 8.447, p < .05$.

Performance was significantly different for each memory load, thus showing that the accuracy of recognizing a stimulus was adversely affected by increasing the number of stimuli presented during the trial. The significant main effect of memory load on performance can be seen in Figure 7, $F(2, 19) = 154.671, p < .05$.

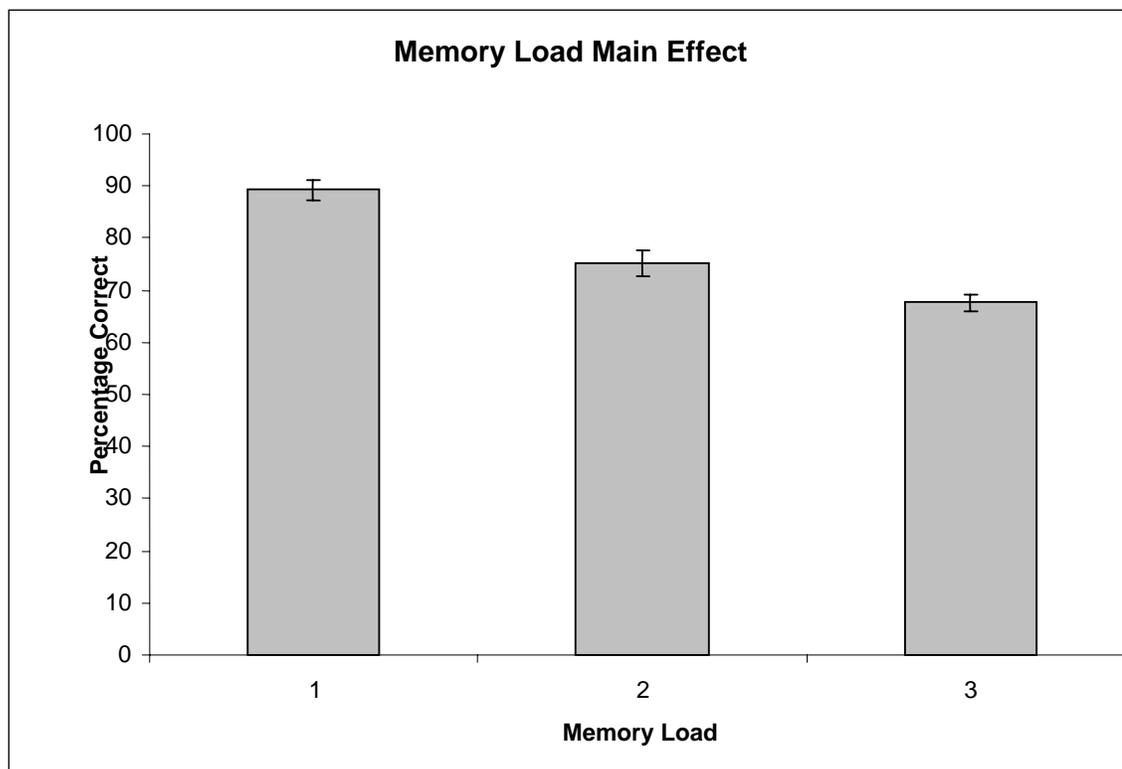


Figure 7: Graph of Memory Load Main Effect.

The effect of memory load on recognition accuracy performance.

In the pairwise comparisons, a memory load of one item was recognized more accurately than when two items or three items were presented. Additionally, from the pairwise comparisons, performance on a memory load of two presented items differed significantly from performance on a memory load of three items. The main effect of

condition was not significant ($F < 1, p > .05$), suggesting that concurrent tasks did not affect performance. Performance during the control condition did not differ from the articulatory suppression or verbal load conditions. No difference existed between the articulatory suppression and verbal load condition. None of the interactions were significant, with all $F < 1, p > .05$.

As was indicated in the introduction, these performance measures were collected to provide estimates of capacity. Capacity estimates were calculated by using Cowan's K (2001) formula:

$$K = (\text{hit rate} + \text{correct rejection rate} - 1) * N,$$

N = the number of objects presented (memory load)

Capacity was computed for each type of trial. A mixed-design 2 (order) x 3 (condition) x 2 (stimulus type) x 3 (memory load) ANOVA with estimated capacity as the dependent variable was conducted. Capacity differed dependent upon the type of stimuli being presented. The capacity of memory for simple stimuli (mean = 1.02 objects, SE = 0.08) was significantly higher than for complex stimuli (0.88 object, SE = 0.07), $F(1, 20) = 4.86, p < .05$. The main effect for memory load was also significant, $F(2, 19) = 7.24, p < .05$. Performance was significantly different for each level of memory load and this can be seen in Figure 8. From the pairwise comparison, it was determined that capacity estimates of one item (0.89 object, SE = 0.02) was significantly lower than two items (1.01 objects, SE = 0.10) and three items (1.06 objects, SE = 0.10). No significant difference in capacity existed between memory loads of two and three items. The main effect of condition was not significant ($F < 1$), suggesting that concurrent tasks

(articulatory suppression and verbal load) did not affect capacity. None of the possible interactions were significant, all $F < 1$.

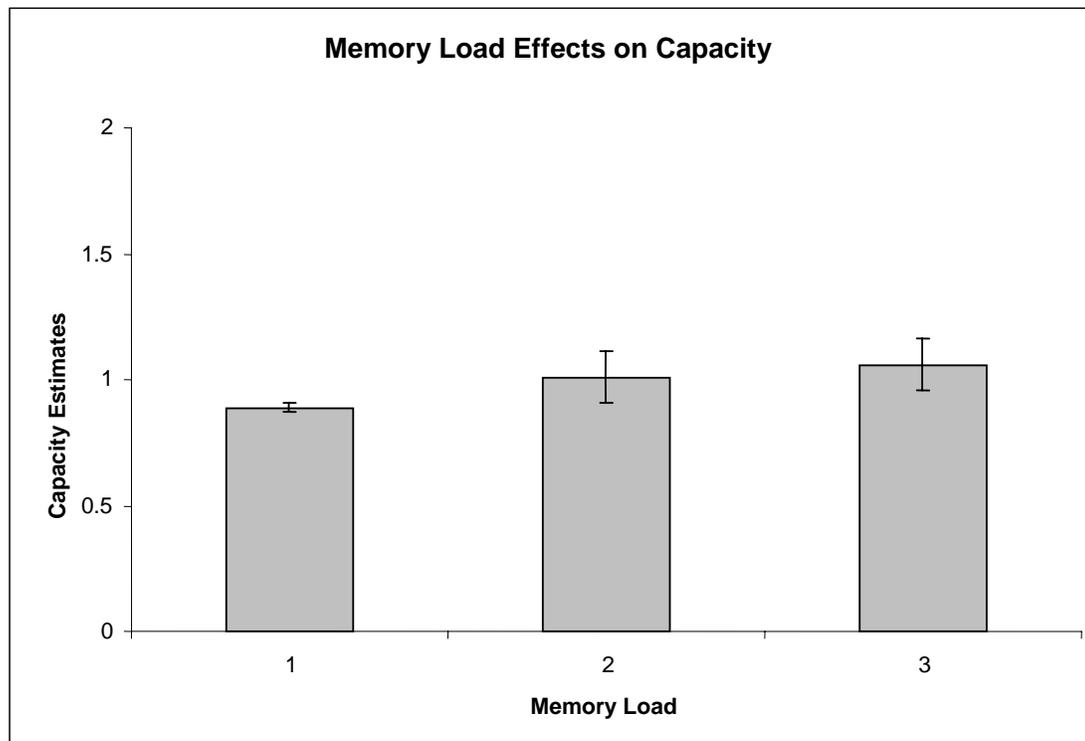


Figure 8: Graph of Memory Load Effects on Capacity

The effect of memory load on capacity estimates (see text for explanation of capacity computations).

Cerebral blood flow velocity data

Cerebral blood flow velocity (CBFV) was calculated by subtracting each participant's average baseline CBFV from the CBFV recorded in one second of stimulus presentation. The baseline average was calculated by averaging the CBFV from two minutes of recording. A two-way 2 (hemisphere) x 2 (correct or incorrect recognition) ANOVA was conducted comparing CBFV in trials answered correctly to CBFV in trials answered incorrectly for both hemispheres. There was no significant difference in CBFV

between trials correctly (mean CBFV = -2.21, SE = 0.63) or incorrectly answered (mean CBFV = -1.93, SE = 0.66), $F(1, 21) = 3.52, p = .075$. There was also no significant difference in CBFV between the right hemisphere (mean CBFV = -2.38, SE = 0.81) and the left hemisphere (mean CBFV = -1.77, SE = 0.83), $F < 1, p > .05$. The interaction was not significant, $F < 1, p > .05$. In the following analyses, average CBFV was combined for correct and incorrect trials.

CBFV in the first block (control 1) was compared to the last block (control 2). Control 1 was the first 60 trials performed and was in the control condition, thus did not contain a concurrent task. Control 2 was the last 60 trials and also was in the control condition. A two-way 2 (hemisphere) x 2 (block) ANOVA was conducted comparing CBFV in control 1 to CBFV in control 2 for both hemispheres. CBFV was significantly different between blocks, with CBFV significantly faster relative to baseline in control 1 (mean CBFV = -0.139, SE = 0.51) than control 2 (mean CBFV = -3.418, SE = 0.92), $F(1, 21) = 14.92, p < .05$. CBFV did not differ significantly between hemispheres, $F < 1, p > .05$. In future analyses with CBFV as the dependent variable, the control condition was not collapsed across blocks.

A mixed-design 2 (order) x 4 (condition) x 2 (stimulus type) x 3 (memory load) x 2 (hemisphere) ANOVA with the change in CBFV as the dependent variable was conducted. CBFV was significantly slower for simple stimuli (-2.168) than complex stimuli (-2.028), $F(1, 20) = 4.432, p < .05$. The brain was more activated for complex objects than simple objects.

An additional level was added to the condition variable as the two control blocks could not be collapsed together. Thus, the condition variable included 4 levels that were:

control 1 (mean CBFV = -0.029, SE = 0.531), articulatory suppression (AS; mean CBFV = -2.538, SE = 0.901), verbal load (VL; mean CBFV = -2.290, SE = 0.753) and control 2 (mean CBFV = -3.535, SE = 0.913). The main effect of condition was significant, $F(3, 18) = 4.597, p < .05$. In the pairwise comparisons, control 1 differed significantly from VL and control 2, $p < .05$. The pairwise comparison of control 1 and AS approached significance, $p = .066$. No difference existed between AS, VL and control 2. The brain had the highest activation level in control 1. Activation decreased in the articulatory suppression condition and then decreased slightly more for the verbal load condition and control 2.

The Condition-by-Order interaction was also significant, $F(3, 18) = 4.597, p < 0.05$, and this interaction is displayed in Figure 9. CBFV was similar for both orders of control 1 conditions, but this was expected because participants in both orders would perform this condition first. CBFV dropped from the second block to the third block, regardless of which task (AS or VL) was in the second block. The control 2 condition was faster when it followed AS than when it followed VL. The three-way interaction of condition by hemisphere by order was significant, $F(3, 18) = 3.201, p < .05$. This effect will be examined further below.

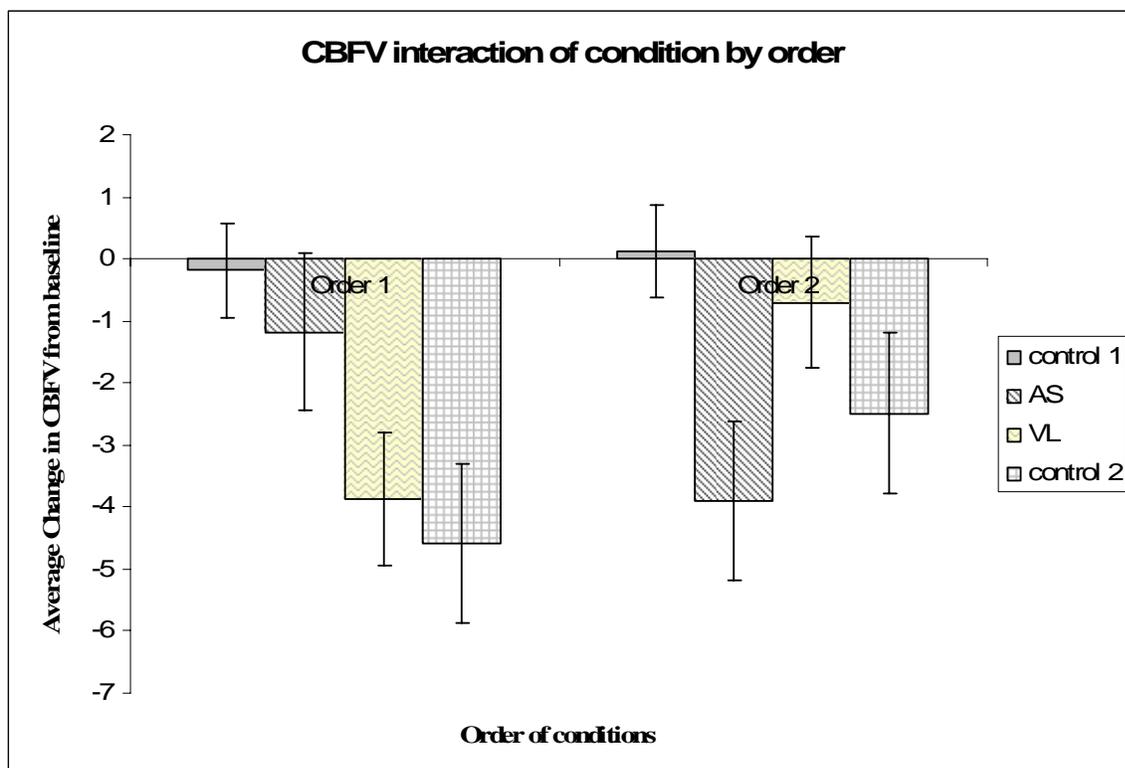


Figure 9: Graph displaying the CBFV interaction of condition by order.

The interaction of Condition-by-Order. Change in CBFV from baseline is shown on the Y axis.

I hypothesized that CBFV would predict memory load and capacity levels by varying as a function of the task performed and as a function of the difficulty of the task. Although there was not a main effect of memory load, the two-way interaction of condition by memory load was significant, $F(6, 15) = 4.177, p < .05$, and it is presented in Figure 10. CBFV decreased as memory load increased in the control 1 condition, whereas in the control 2 and VL conditions, CBFV remained relatively stable. In the AS condition, CBFV increased from one object to two objects and then dropped with three objects.

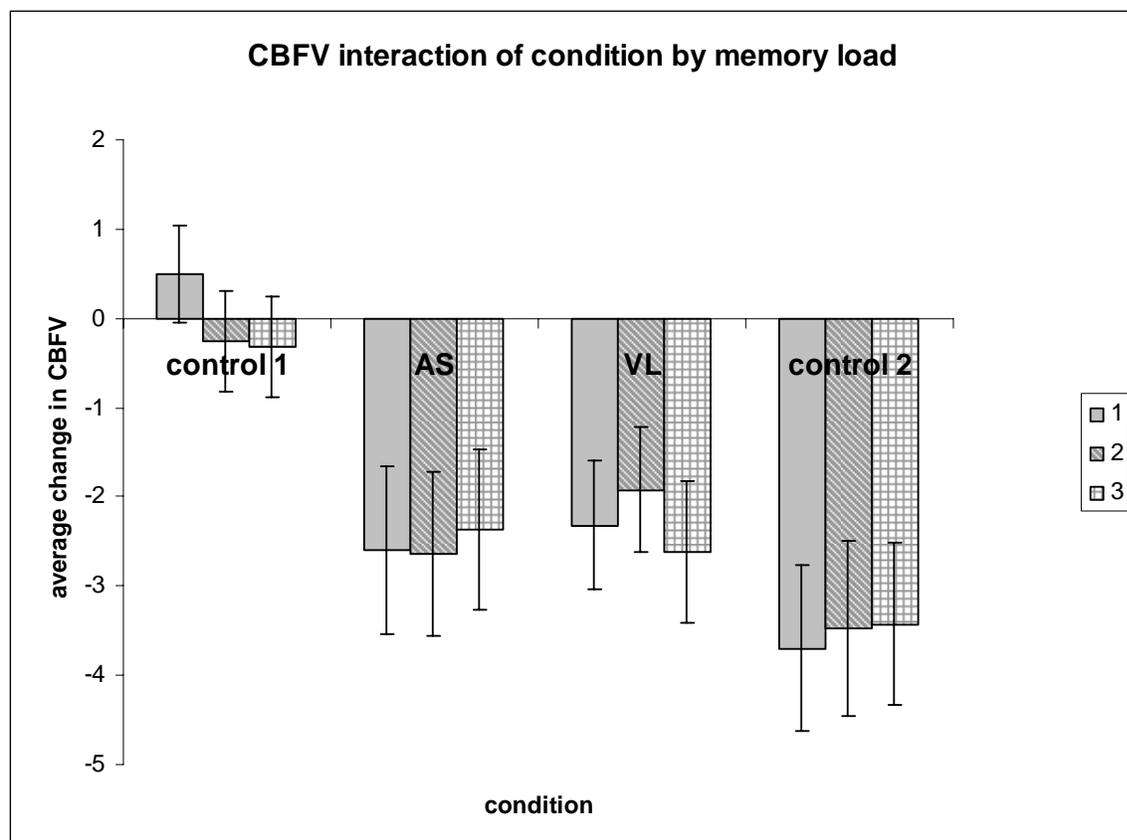


Figure 10: Graph displaying CBFV interaction of condition by memory load.

Change in CBFV from baseline is shown on the Y axis and type of condition is shown on the X axis. Memory load of 1, 2 and 3 is shown in the legend.

All other main effects and interactions were not significant ($F < 1.00, p > .05$).

This suggests that brain activation was highest in the control 1 with a memory load of 1 item. For the other conditions, a memory load of 1 item had the lowest amount of activation, although memory load of 2 and 3 had higher amounts of activation than memory load 1, they were similar.

Further analysis was conducted to delve into the interactions. As the variable of condition was included in each interaction, each condition was analyzed separately. Separate mixed-design 2 (order) x 2 (stimulus type) x 3 (memory load) x 2 (hemisphere)

ANOVAs were conducted to analyze the simple effects from the interactions. In the control 1 condition, no main effects or interactions were significant ($F < 1.00, p > .05$). In the VL condition, the main effect of stimulus type was significant, $F(1, 20) = 18.436, p < .05$. CBFV was slower for simple objects ($-2.33, SE = 0.75$) than complex objects ($0.86, SE = 0.02$). In a similar trend as the VL condition, stimulus type approached significance, $F(1, 20) = 3.548, p = .07$, in the AS condition. CBFV was lower for simple objects ($-2.75, SE = 0.633$) than complex objects ($-2.32, SE = 0.614$). All other main effects and interactions were not significant ($F < 1, p > .05$). Similar to the results in the AS condition but with larger differences between stimulus types, CBFV was lower for simple objects (-2.33) than complex objects (0.86). All other main effects and interactions were not significant ($F < 1, p > .05$). The control 2 condition was similar to control 1 with no significant main effects or interactions ($F < 1.00, p > .05$).

A regression of average right CBFV and average left CBFV was used to test whether individual differences in CBFV predicted performance (average percentage correct, across trials and conditions). Overall mean of performance was 77.4%, $SD = 8.3\%$. Performance ranged from a minimum of 57% to a maximum of 91%. This regression was not significant, $r(2, 19) = 0.182, F < 1.00; p > .05$. A regression of average right CBFV and average left CBFV was used to test whether CBFV would predict capacity. Average capacity was 1.09 objects, $SD = 0.33$. Performance ranged from a minimum of 0.27 object to a maximum of 1.63 objects. This also was not significant, $r(2, 19) = 0.182, F < 1.00, p > .05$.

Discussion

VSTM Capacity: Fixed or Flexible?

The results in this study, both with respect to performance and CBFV, support the flexible resource model, not the object-based model of VSTM. Performance on the change-detection task and the capacity estimates computed from that performance were significantly different for the two levels of complexity. Recognition accuracy was significantly better for simple than complex items, indicating that VSTM can hold significantly more simple objects than complex objects. The object-based theory would have been supported only if performance was the same for both complex and simple objects—that is, if VSTM appeared to hold some fixed number of visual stimuli, irrespective of the nature of those stimuli. Table 1 lists the hypotheses and findings.

Table 1

Table of hypotheses and results found.

Hypothesis	Supported?	Interpretation
Removal of the ability to use the phonological loop through articulatory suppression would not affect performance.	Yes	The phonological loop did not inflate VSTM capacity.
Removal of the ability to use the central executive through a concurrent verbal load would decrease performance.	No	The central executive was not used by VSTM.
I also hypothesized that capacity would vary according to stimulus complexity, as predicted by the flexible resource theory	Yes	The flexible resource theory was supported as simple objects had larger capacities than complex objects. CBFV was faster for complex objects than simple objects, thus brain activation was higher for complex objects.
I hypothesized that CBFV would increase with increases in stimulus complexity	Yes	

I anticipated that as memory load increased, accuracy would decrease	Yes	The more items that are presented, the lower performance levels.
CBFV would increase as memory load increased until an asymptotic level	No	CBFV did not vary for memory load as already at asymptotic level
CBFV would asymptote and this would correspond with capacity.	Yes	Capacity was at one object thus the asymptote was reached under any memory load.
The right hemisphere would be more active for the change-detection task	No	There was no significant differences between hemispheres.
The concurrent tasks that use verbal tasks (articulatory suppression task and concurrent verbal load task) should cause the left hemisphere to be more active	No	There was no significant differences between hemispheres.

These data suggest that capacity in VSTM is limited by the complexity of the objects as well as the number of objects presented, and thus the number of items that can be retained in VSTM is a function of the amount of information in each item. This result replicates Alvarez and Cavanaugh (2004), although they measured complexity through search rate whereas complexity was defined objectively by the number of turns in the random polygon shapes in the present study.

The analysis of brain activation, as indicated by fTCD, provides further evidence to support the flexible resource model above the object-based model. Cerebral blood flow velocity differed significantly between the two levels of stimulus complexity, with faster blood flow when participants were attempting to remember complex versus simple stimuli. This suggests that mental workload was higher when the to-be-remembered stimuli were more complex. The blood flow effects, like the performance differences, show that all stimuli are not recognized equally as might be suggested by the object-

based model where the number of slots is fixed and each slot can hold all of any one stimulus.

VSTM Capacity: One Item or Four?

The capacity of VSTM had an upper limit of about one item in the present results. The limit in this study replicated the findings of Phillips and Christie (1977) and Barrett and Washburn (2005, 2006a,b), but was much lower than was the limit of about 4 items that has also been reported (Todd & Marois, 2004; Vogel et al, 2001). However, the stimuli used in these latter studies were simple items such as colored squares. In contrast, Phillips and Christie used complex checkerboard stimuli. Barrett and Washburn used complex shapes. Similarly, even the simple polygons in the present study could be considered more complex than colored blocks, and this may account for the smaller capacity estimates in the present study. If so, this suggests another demonstration of how VSTM capacity varies on the basis of stimulus complexity, such as was discussed above regarding the comparison of simple and complex polygons. Of course, memory loads greater than three were not presented in the present study, and thus it was impossible for participants to produce capacity estimates as high as four items. This was done purposefully as previous research where random polygons were used as stimuli produced capacity estimates between one and two items (Song & Jiang, 2006). This design decision was validated by the present data, which show clearly that participant cannot remember even two random polygons accurately.

Similarly, the effects of memory load on performance and on CBFV suggest a small VSTM capacity. If VSTM could hold 2 or more items effectively, one would expect recognition accuracy to be equivalent while CBFV increased as the number of

items to be stored increased. In contrast, CBFV did not differ significantly between memory loads. Although it is risky to draw inferences from null findings, the CBFV data suggest that the brain activation or mental workload associated with remembering one item in VSTM was about the same as for remembering 2 or 3 items. The mental activity required to remember one polygon was as great as that observed when participants had to remember more than one stimulus. Although an interaction between memory load and concurrent-task condition was observed for CBFV, the effect of memory load on CBFV was no longer significant in any of the conditions when the conditions were analyzed separately. Compare this finding to those reported by Xu and Chun (2006), who concluded that activation increased with the number of items presented and asymptote at the capacity limit. Those authors found that activation (measured using fMRI) differed for memory loads only for simple shapes and not for complex shapes. This was explained by the capacity differences. Capacity for simple shapes was not reached in the lower memory loads; thus, different levels of activation were observed for the number of stimuli in memory. However, for the complex shapes the capacity was reached with the lower memory loads; therefore, activation was at the level of asymptote for all memory loads. This is similar to the findings in the current study. As suggested above, the maximum capacity was around one object for simple polygons and less than one for complex polygons. Therefore, CBFV was asymptotic at one-item memory loads.

Accuracy on the change-detection task decreased significantly as memory load increased, and did so at the approximate rate that would be predicted if VSTM capacity = 1 flexible slot. Figure 11 shows predicted recognition performance as a function of capacity. That is, it shows what change-detection performance should look like if VSTM

is limited to 1, 2 or 3 items respectively (with the assumption of some error, so that even a single item is remembered correctly only 89% of the trials). The figure also shows observed performance from the present results, which approximates (albeit imperfectly) the “VSTM capacity = 1 item” predictions.

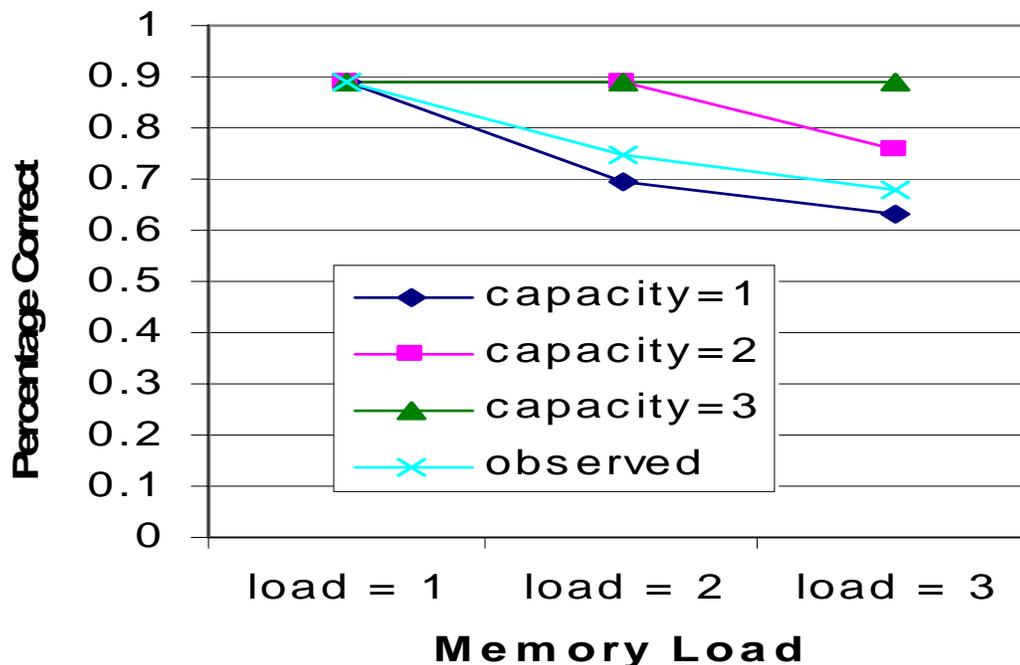


Figure 11: Comparison between predicted percentage correct per capacity levels.

Graph displays expected percentage correct at each memory load for each capacity level.

Percentage correct or level of performance is shown on the Y axis.

To reiterate, recognition accuracy decreased as memory load increased, but the capacity estimates increased as memory load increased, whereas CBFV did not change with changes in memory load. What do these results suggest about limits in the number of visual items that can be remembered over brief delays? Performance when only one to-be-remembered object was displayed was generally excellent, although not perfect (at

about 89% accuracy). Performance fell to 75% correct when two items were displayed. If capacity was one item, performance should have been about 70% (i.e., 89% for one item and around 50% for the other); but if capacity was two items, performance should have been similar to performance with a memory load of one object. Thus, when more than one stimulus was presented, it appears that VSTM can hold information about more than one item, but not even that one item perfectly.

One concern when estimating VSTM capacity was to eliminate any contribution by verbal encoding and rehearsal. Generally, concurrent-task condition did not affect the independent measures in this study, suggesting that participants in the control condition were using the VSTM mechanisms without contribution from structures or processes that become active during the verbal-load and articulatory-suppression conditions. The current study was focused on visual-object memory, but produced no evidence that verbal memory was also utilized in the task, as performance was not affected by engaging the phonological loop through articulatory suppression. As no interference of articulatory suppression was also found previously for spatial information (Morey & Cowan, 2004; 2005; Eng et al, 2005), the findings in this study can be used to support that the phonological loop is not necessarily utilized in visual-object memory. Further evidence that language was not supporting VSTM in this study comes from the fact that the left hemisphere, which is known for being the typical hemisphere for language processing (Milner, 1971; Kinsbourne, 1978), was not consistently dominant over the right hemisphere in the present CBFV data.

Performance also was not altered when the central executive was engaged in a concurrent verbal load task. In previous research, tasks engaging the central executive in

this way were detrimental to performance on change detection tasks (Allen et al., 2006; Cocchini et al., 2002; Morey & Cowan, 2004; 2005). Two potential reasons could explain the difference between previous findings and the current study. The current study was focused on visual-object memory instead of spatial memory of the location of objects, as in the previous studies. Object memory may require fewer resources from the central executive than spatial memory. Another possible explanation is that the concurrent load of seven digits used in the present task simply did not sufficiently tax the central executive. However, this possibility seems unlikely because previous researchers also used a concurrent memory load of seven digits and reported impaired performance (Allen et al., 2006; Cocchini et al., 2002; Morey & Cowan, 2004; 2005). Additionally, in the current study rehearsal of the digits was aloud, a variation that has been shown to decrease performance when silent rehearsal did not decrease performance (Morey & Cowan, 2005). From the results, I conclude that it is possible to recognize visual images after brief delays even if the attentional resources of the central executive in working memory are otherwise allocated.

Limitations of the current study

In this study, performance and brain activity varied as a function of object complexity. Manipulations of memory load suggested that VSTM has a capacity limit of approximately one item, although capacity varied with the complexity of the objects. This result was consistent across dependent variables (change-detection accuracy and CBFV). This is the first study in which fTCD provides convergent evidence regarding the characteristics of this cognitive construct. However, there were several limitations and curiosities about the CBFV data that must be acknowledged.

The first curiosity is that a majority of the mean CBFV values were negative, thus CBFV was slower during the task than the baseline levels. The measurement of CBFV used in the study was a mean change in CBFV calculated by subtracting the baseline average from the CBFV recorded during the task. The purpose of using mean change in CBFV was to remove individual differences in resting rates of blood flow and signals. One would expect participants to be more cognitively active when attempting to remember the stimuli than in the resting baseline period, but this was not the case. The increased levels of activation during baseline could have been caused by multiple different factors, from heightened activation from previous interaction with the experimenters to distress. It is noteworthy that the findings in this study deal in comparisons between CBFV for varying types of tasks in the same session; therefore the relative differences reported here unaffected by the elevated rates of CBFV in the baseline. Nevertheless, the reduced blood flow velocity during the change-detection task relative to baseline is perplexing and potentially challenging to the very assumptions of fTCD.

Second, no significant difference was found between CBFV on accurate and inaccurate trials. CBFV was recorded during the retention interval of each trial, but does not predict whether responses were accurate on the trial. This is contrary to the hypothesized result that CBFV would predict performance, which followed from studies like Todd and Marois (2004), who found different levels of amplitude in ERPs between correct and incorrect trials. A potential explanation for the difference between the results in their study and the current one is the capacity of approximately one found in this study. If capacity is about one, the expectation would follow that trials with VSTM overloaded

beyond capacity and would result in chance levels of performance. One would not expect different activation levels when participants are working at chance levels of accuracy. That is, the mental workload should not be greater for accurate than for inaccurate responses on any trial in which participants were just guessing—as was likely the case on many trials from the present study in which memory load exceeded one item. This potential explanation is undermined however by the fact that CBFV did not differ between accurate and inaccurate responses even when the memory load was one. This may simply reflect the spatial limitation of fTCD (discussed below), as it was impossible to disambiguate brain activity associated with effective memory performance from brain activity that may have distracted the participant from the task (e.g., thinking about homework) and compromised recognition accuracy.

Similarly, CBFV did change under conditions in which no performance changes were observed. Examination of the condition effects on CBFV, one can see that CBFV slowly decreased throughout the experiment. In vigilance research, CBFV has been found to vary across the length of the vigil (Barrett & Washburn, 2006a,b). This explanation would also be supported by CBFV being faster in the first control condition than any other condition, the drop in CBFV from block 2 to block 3, regardless of the concurrent task, and by the significant decrease in CBFV for the final 60 trials in the control 2 compared to the first 60 trials in the control 1. However, control 2 condition CBFV was faster when it followed AS than when it followed VL. This combination of results was unexpected and need further research to delve into the possible implications.

CBFV did not differ between hemispheres; however, there was a significant interaction between condition, order and hemisphere for CBFV. Once more, when the

CBFV was analyzed in each condition, the interaction between order and hemisphere was no longer significant. Thus, activation in the brain was not lateralized consistently to one hemisphere over the other in any of the conditions, including the articulatory suppression and verbal load conditions that should have resulted in more left-hemisphere activation. Although this finding is contrary to the hypothesized result, it is consistent with previous research on visuospatial tasks such that the right hemisphere was not dominant over the left hemisphere, but inconsistent as the left hemisphere was not dominant over the right during the verbal conditions (Bulla-Hellwig et al., 1996; Cupini et al., 1996). Therefore, the findings do not support the verbal-spatial theory about lateralization in brain activation. One possible explanation for the lack of lateralization was that focusing attention by the central executive overwhelmed the hemispheric differences that would have existed. Attention has been examined closely using fTCD, however it focused on the effects of different types of attention and not lateralization per se (Barrett & Washburn, 2006a,b). Although some visuospatial tasks show right lateralization whereas others do not show right dominance in CBFV, future research should focus on attention tasks across different modalities to determine whether fTCD is affected by this variable.

Although the CBFV data in the present study generally support and strengthen the conclusion drawn from the performance measures, these curious findings limit the enthusiasm with which fTCD can be recommended for future studies. As noted above, another major disadvantage of fTCD is low spatial resolution. The basal arteries profuse to large areas of the brain; thus, activation cannot be determined for specific brain locations. However, this limitation is of little consequence in the present study as the level of overall activation, rather than the activation of any specific brain regions, was the

focus of this study. Stroobant and Vingerhoets, (2000) noted another limitation of fTCD, indicating that it may not be sensitive to subtle changes from the small branches of arterioles that perfuse small cortical areas. As the results were significant in this study, this limitation was not an issue. The largest disadvantage was related to the individual differences in the size of the ultrasonic window, and the thickness of the window can cause the fTCD to be unable to acquire a signal. fTCD research excludes participants without the ultrasonic window, usually older individuals, because fTCD cannot measure CBFV without the ultrasonic signal. This exclusion removes a potentially important proportion of the population. In the current study, 14 of the 36 participants were not included due to the inability to find the signal in both hemispheres. Nevertheless, it is unlikely that this confounded the study. Previous reports have suggested that performance did not differ between participants who had signals recorded compared to participants without signals recorded (Duschek & Schandry, 2003; Hitchcock et al., 2003).

Conclusion

This study was focused on object memory in visual short-term memory and potential causes of the small level of capacity. Performance and blood flow measures suggest that VSTM is limited to about one visual stimulus, although this estimate is affected by the complexity of that item. From these results, it appears that variability in published estimates of VSTM capacity are largely a function of the complexity of the to-be-remembered objects. The present estimates of capacity fell far below the level proposed by the object-based model with fixed, four slots. The results therefore favor the flexible resource model in which VSTM can hold the information in one complex image, or less information per stimulus about multiple complex items, but perhaps enough

information accurately to recognize several very simple objects. In addition to this, performance was also not affected by concurrent tasks of articulatory suppression or verbal load. Visual short-term object memory does not rely on other mechanisms in working memory (e.g., phonological loop or central executive) to increase capacity.

References

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ⁱ Memory for a list of visuospatial stimuli is improved if the stimuli can be recoded verbally and rehearsed (Paivio, 1990). Silverberg and Buchanan (2005) found that participants demonstrated higher retention for easily verbalized stimuli. In the second experiment of that study, verbal interference mitigated the effect of easy verbalization of the stimuli, but visual interference did not remove the effect. Similarly, verbal memory was found to support VSTM when utilizing object memory but not spatial recognition (Postle, D'Esposito & Corkin, 2005).

However, a concurrent verbal load of two digits subvocally rehearsed (Vogel, Woodman & Luck, 2001) and six digits rehearsed aloud (Eng et al., 2005) did not reduce the amount of visual information that could be retained in VSTM. Verbal memory also had no effect when different types of stimuli were used (Eng et al., 2005). Similarly, concurrent tasks of rehearsal of the participant's phone number or articulatory suppression had no effect on performance (Morey & Cowan, 2004). Whether the stimuli were letters presented normally or letters mirror-reflected across the horizontal axis made no difference to change detection performance, but it did impair letter identification (Pashler, 1988).