OUT OF SIGHT, OUT OF MIND? THE EFFECT OF VISUAL FIELD OF VIEW
RESTRICTIONS ON WORKING MEMORY

by

Derek Pasma

A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements
for the degree of

Doctor of Philosophy

in

Psychology

Carleton University
Ottawa, Canada

© 2016 Derek Pasma

Abstract

Visual field of view (FoV) restrictions have been found to impair performance on a variety of tasks, including estimating distances, locomotion, target tracking, and the development of spatial representations, as well as in specific domains such as aviation. Explanations for these impairments have largely focused on the restrictions to the physical environment and lack of peripheral information available to the user. The goal of this thesis was to provide a more complete account of these performance impairments by examining whether restrictions to the visual field affected working memory, a cognitive component responsible for the maintenance, integration, and retrieval of visual information.

Three experiments were conducted in which the impact of restricted FoV on memory for simple geons was examined. In Experiment 1, restricting FoV was shown to decrease performance on a Geon Memory Task (GMT). Experiment 2 established the relative difficulties of four secondary tasks commonly used in dual-task paradigms (counting, counting/tapping, spatial tapping, and random tapping) to tax individual working memory components and used as secondary working memory tasks in Experiment 3. Experiment 3 examined the relationship between FoV, working memory, and performance on the GMT using a dual-task paradigm. Results from Experiment 3 were consistent with those of Experiment 1 and further supported the hypothesis that FoV negatively affects phonological and visuo-spatial working memory. The central executive was not negatively affected by FoV restrictions. The present findings suggest a more complete account of the impact of FoV restrictions than the lack of peripheral information alone and offer important contributions to the working memory literature.

Acknowledgements

First, thank you to my supervisor, Chris Herdman, for providing support, guidance, and mentorship, as well as the resources to carry out my research. Thank you also for supporting me in my decision to take time off to pursue my flying career and for making time for me when I came back to finish. Thank you to Matt Brown for your time and guidance throughout my time at Carleton, particularly when I showed up with little-to-no warning between my flying courses looking for feedback or edits. Your feedback in all stages of my dissertation was invaluable. Thank you to Andy Staples and Jon Wade for all your work on the technical aspects of this project, and for taking random calls and requests for help. Thank you to the rest of the ACE lab for assistance, encouragement, and friendship.

Thank you to my committee, in particular to Jo-Anne LeFevre, John Logan, and Avi Parush. Thank-you, Jo-Anne, for your input on the MLM and encouraging me to step outside of my comfort zone to learn something new. Thanks to Avi for your involvement early in this project. Thanks to John for stepping in and filling Avi's position on the committee with little notice to allow me to finish.

Completion of this project would not have been possible had it not been for a number of people in the Royal Canadian Air Force in direct control of my schedule. Thank you to Mary-Frances Jasper, Conor Murphy, and Dean Rood. Without your support and backing, there is no way I would have been able to finish. Thank you also to my various chains of command at the Rescue Coordination Centre, 1 Wing HQ, and 436 (T) Squadron for the support and flexibility of schedules and courses.

Thank you to my Mom and Dad for teaching me to work hard, to take pride in my work, for teaching me to stick with something till the end, and for encouraging me along the way. Though no one in the academic world *really* expected me to finish after being away, your model of hard work and dedication made this a non-issue. At no point while I was away did I consider giving up an option. I owe that perseverance to you. Thank you also to the rest of my family and friends for continuous support and encouragement.

Most of all, thank you to my wife, Rikki. Your love, support, encouragement, and patience have allowed me to succeed. I'm sorry for countless stacks of paperwork and books in the office - and also for not cleaning the basement and the garage for the last little while. Now that I am finished, I promise to clean up the office area, clean the garage, organize my tools, make sure the basement stays clean, finish the stairs on the deck, put the second coat of paint on the hallway and kitchen, retile the front entrance, take out the closet and build a coat rack, install wainscoting in the front hallway, paint that big wall, install a new hot water heater, put the doorknobs on the closet doors I hung last year, fix the drainage issue in the yard...and the basement, clean out the closet, build some bedrooms in the basement, throw out some of the junk in the basement that I haven't looked at in years, and so on. I love you!

Finally, to my daughter, Gwen - Thank you for sleeping through the night...and for being an all-around awesome little person. This dissertation is dedicated to you. Know that with hard work and perseverance, things that seem impossible become possible.

Table of Contents

Abstract	ii
Acknowledgements	iii
Table of Contents	iv
List of Tables	viii
List of Figures	ix
CHAPTER 1: INTRODUCTION	11
The Human Visual System and Field of View	12
Restricted Field of View and Flight Performance	14
Effects of Restricted Field of View on Performance	20
Walking/Locomotion	20
Visual Search and Target Tracking	22
Distance Estimation	24
Spatial Representations	27
Summary	29
Working Memory	30
The Phonological Loop	31
The Visuo-spatial Sketchpad	33
The Central Executive	34
The Episodic Buffer	36
Field of View Restrictions and Working Memory	37
Present Research	42

CHAPTER 2: EXPERIMENT 1	44
Method	45
Participants.....	45
Stimuli and Apparatus.....	45
Geon Memory Task	47
Design and Procedure	50
Measures	50
Results.....	51
Number of Attempts to Recreate the Scene	51
Proportion of Geons Replaced Incorrectly	52
Geon Selection Accuracy.....	52
Geon Replacement Accuracy.....	52
Discussion.....	54
CHAPTER 3: EXPERIMENT 2.....	55
Method	57
Participants.....	57
Stimuli and Apparatus.....	57
Experimental Design and Procedure.....	58
Results.....	59
PDT Responses	59
Working Memory Tasks	61
Discussion.....	65
CHAPTER 4: EXPERIMENT 3.....	68

Methods	70
Participants.....	70
Stimuli and Apparatus.....	70
Design and Procedure	70
Results.....	73
Number of Attempts to Recreate the Scene	74
Proportion of Geons Replaced Incorrectly	75
Proportion of Distractor Geons Selected	76
Geon Replacement Accuracy.....	78
Multilevel Linear Model	81
Working Memory Task Performance	93
Discussion.....	97
CHAPTER 5: GENERAL DISCUSSION.....	102
Theoretical Account.....	104
FoV and Phonological and Visuo-spatial Working Memory	104
FoV and the Episodic Buffer	109
FoV and the Central Executive.....	111
Learning.....	112
Conclusions.....	113
References.....	116

List of Tables

Table 1. Model Summaries: Unconditional Models.....	85
Table 2. Model Summaries: Piecewise Models.....	87
Table 3. Mean Scores (<i>SD</i>) of Randomness Measures for Experiments 2 and 3... ..	95

List of Figures

<i>Figure 1.</i> Example of a common NVG and circular FoV.....	12
<i>Figure 2.</i> Baddeley's (2000) Working Memory Model.	31
<i>Figure 3.</i> Experimental layout and associated goals. Geon memory task (GMT) is the primary task used in Experiments 1 and 3 and was developed for the present research. .	43
<i>Figure 4.</i> Broad angle display system (BADS).	46
<i>Figure 5.</i> Modified safety glasses to produce (a) 40° FoV and (b) 120° FoV.....	47
<i>Figure 6.</i> Virtual environment with 3D geons.....	48
<i>Figure 7.</i> Bar graphs depicting significant differences between wide and narrow FoV conditions for (a) number of attempts required to recreate the scene; (b) proportion of geons replaced incorrectly; (c) geon placement errors for all attempts; and (d) geon placement errors for first three attempts. Error bars represent standard error.	53
<i>Figure 8.</i> Working memory and PDT response keypad.	57
<i>Figure 9.</i> Key pressing sequence for the spatial tapping task.....	59
<i>Figure 10.</i> Mean PDT reaction times by working memory task. Error bars represent 95% CIs (Loftus & Mason, 1994).	60
<i>Figure 11.</i> Mean response rate per 30-second trial by secondary tasks. Spatial and random tapping tasks had significantly greater generation rates than counting and counting/tapping. Counting/Tapping rates were significantly greater than counting alone. Error bars represent relational 95% CIs (Loftus & Mason, 1994).	62
<i>Figure 12.</i> Mean number of attempts required to recreate the scene by working memory task and load conditions. Error bars represent relational 95% CIs (Loftus & Mason, 1994).	75

<i>Figure 13.</i> Proportion of geons replaced incorrectly with 95% CIs (Loftus & Mason, 1994) depicting a significant Load x FoV interaction in the phonological and central executive working memory conditions.	76
<i>Figure 14.</i> Proportion of distractor geons selected with 95% CIs (Loftus & Mason, 1994) depicting the Load x FoV interaction effect.	77
<i>Figure 15.</i> Geon placement errors with 95% CIs (Loftus & Mason, 1994) depicting the Load x FoV x WM interaction. Phonological and visuo-spatial groups display negative effect of FoV in addition to that of a secondary task.	79
<i>Figure 16.</i> Geon placement errors for the first three trials with 95% CIs (Loftus & Mason, 1994) depicting Load x FoV x WM interaction.	80
<i>Figure 17.</i> Raw data depicting trajectories of geon placement errors by attempt number for all participants.	83
<i>Figure 18.</i> Predicted trajectories of geon placement errors for wide (top) and narrow (bottom) FoV conditions.	90
<i>Figure 19.</i> Predicted geon placement errors as a function of attempt number and FoV condition for the visuo-spatial working memory group. Magnitudes of placement errors in narrow FoV condition were initially greater, but decreased quicker than those in the wide FoV condition over the first three attempts.	92
<i>Figure 20.</i> Example view of visual scene with no FoV restriction (a) and simulated FoV restrictions (b). Under normal viewing conditions, the viewer may scan globally obtaining geon and spatial information on initial glances. Under restricted FoV conditions, attention may be focused quickly on geons of importance, neglecting the spatial relations between them.	108

CHAPTER 1: INTRODUCTION

In human vision, field of view (FoV) refers to the area of the visual field in which information can be extracted from a visual scene in a single glance and without movements of the eyes or head. This area is approximately 200° horizontal by 130° vertical (Arthur, 2000). Under normal circumstances, FoV is rarely given a second thought. However, when it is reduced, consequences can range from subtle accommodation to debilitating depending on the magnitude of the reduction, as well as the context in which they occur. Reductions in FoV may occur for many reasons. For example, medical conditions such as glaucoma may result in an acute reduction in FoV. Reduced FoV has been linked to age with evidence suggesting that reduced FoV in the elderly may be attributed to changes in the visual sensory system, as well as to age-related changes in higher cognitive functions (Sekuler & Ball, 1986; Sekuler, Bennett, & Mamelak, 2000). FoV is also reduced when wearing a motorcycle helmet or when wearing thick-rimmed glasses. In these situations, FoV reductions are usually minor and can be accommodated with little or no impairments. In other situations, large reductions in FoV may be a byproduct of technologies that offer other important benefits to the user. In these situations, significant training and experience is required to adequately perform tasks under these conditions. One such example, and one of personal interest as a military aviator, is that of night vision goggles (NVGs).

Night vision goggles have provided both military and civil aviation communities with important advantages. NVGs magnify ambient light to allow the user to see the environment in very low-light conditions and their use has dramatically improved night capabilities of both fixed and rotary-wing pilots in important tactical and search and

rescue operations. Current NVGs (e.g., see Figure 1) limit the pilot to a FoV that is approximately 40-50 degrees (Jennings & Craig, 2000). Research has shown that restricting FoV can decrease a pilot's situation awareness (SA) and increase their mental workload (Wickens, Thomas, & Young, 2000). This suggests that in addition to the effects of limiting the availability of information to the visual sensory system (e.g., Winterbottom, Patterson, & Pierce, 2006), reductions in FoV affect high-level cognitive functions that are engaged by users of field-restricting technologies when forming a mental representation of the environment. To this end, the objective of the present thesis was to examine how FoV restrictions affect working memory and its subcomponents.

Figure 1. Example of a common NVG and circular FoV.

The Human Visual System and Field of View

Winterbottom et al. (2006) suggest that the impairments caused by FoV restrictions can be explained in terms of the neuroanatomical makeup of the visual system. The human visual system consists of two regions: focal (foveal) vision and ambient (peripheral) vision. Foveal vision is produced by activation of the fovea centralis; a small region of the retina consisting only of cone cells. Cone cells are one of two types of photoreceptors that make up the retina and are responsible for all high-

resolution vision. The focal area has a visual field of approximately 2 degrees. Peripheral vision, on the other hand, contains primarily rod cells. Rods are photoreceptors that are highly sensitive to light but are less sensitive to detail. The peripheral field consists of the entire FoV that is not foveal. Focal vision is responsible for fine detail and object recognition while peripheral vision is important for spatial orientation within the environment (Leibowitz, Shupert, & Post, 1984).

Neuropsychological research has shown that two separate pathways carry visual information to the brain: the magnocellular and parvocellular pathways. The parvocellular pathway carries visual information from the fovea while the magnocellular pathway carries peripheral information. Consistent with the role of focal and ambient vision, the parvocellular pathway is responsible for fine detail and object recognition (i.e., the ‘what’ pathway) whereas the magnocellular pathway analyzes motion and is responsible for spatial processing (i.e., the ‘where’ pathway; Milner & Goodale, 1993; Winterbottom et al., 2006). Thus, when using technologies that limit the visual field (e.g., NVGs), object identification may be preserved, but the ability to orient one’s self in space or make accurate judgments about the locations of objects in space may be compromised due to a lack of peripheral vision and, consequently, a lack of magnocellular pathway activation.

The goal of this thesis was not to examine the effect of FoV restrictions on pilots specifically, but rather to examine the effects of FoV on working memory in the broader population. However, given the breadth of research that has explored the effect of FoV on pilots in the flight environment, the following section will review research conducted on

pilots, specifically, before reviewing more fundamental research of the general population.

Restricted Field of View and Flight Performance

Given the use of NVGs in routine night operations, it is important to explore and understand the effects of FoV restrictions on flight performance. Understanding how FoV restrictions affect the human operator is even more critical given the expectation that NVGs will begin to become more prevalent in the general aviation community within the next decade. Further, the magnitude of the effect that restricted FoV has on flight performance likely depends on the specific flight tasks and domains in which they are employed (e.g., Estock, Alexander, Stelzer, & Baughman, 2007; Gibbs, Hughes, Meehan, & Clark, 1996). For example, low-level flying tasks with rapidly changing environments are more likely to be affected by FoV restrictions than high altitude maneuvers where rapidly changing visual cues are not as important or prevalent. In rapidly changing environments, it may be difficult for pilots to integrate the information and maintain accurate SA of their aircraft. Restricting FoV may have a larger impact on rotary-wing aircraft flight performance than on fixed-wing aircraft given that the flight maneuvers of the former (e.g., assessment of drift during a hover or in hovering turns) are more dependent on specific visual reference points than those of fixed-wing aircraft. The following section will review research on the effects of FoV in various flight applications. In addition to FoV restrictions caused by NVGs, the review presented below includes research conducted on the width of flight simulator visual displays, including those afforded by head mounted displays (HMDs). HMDs are optical displays worn by the user whereby a small screen(s) displays visuals directly to one or both eyes. Continual

development of HMDs have increased the FoV of most commercially available HMDs from 40°-50° a decade ago to over 100° today (e.g., Oculus Rift, HTC Vive, StarVR, etc.).

Studies examining the effect of FoV on performance using fighter jet simulators show that restricting FoV increases pilot workload without dramatic flight performance decrements. For example, Kruk and Runnings (1989) examined the utility of a fiber-optic HMD for flight simulation under three restricted FoV conditions (87°, 107° and 127°) for various tasks at high and low altitudes. They found no evidence that FoV restrictions affected performance (e.g., flight performance, air target detection, air-to-air combat). However, the time to attain formation position increased significantly with a reduction in FoV. Despite the lack of significant effects in general flight performance, air target detection, and air-to-air combat data, performance was marginally worse in the 87° condition. Given this finding, the authors suggested that with narrower FoVs, pilots have less reference to the horizon, which decreases their ability to maintain stable control of the aircraft. Furthermore, subjective pilot ratings showed that most pilots preferred the widest FoV display, arguably because of increased workload associated with maintaining good SA under restricted FoV conditions.

Estock et al. (2007) compared flight performance in a high fidelity, wide-FoV (360°) F-16 flight simulator to that in a lower fidelity, narrow-FoV (i.e., three 30-inch Apple LCDs) F-16 training simulator. Objective flight performance data revealed no differences in ability to maintain formation flight as a function of FoV. However, pilots reported greater acceptance and utility of training for the wider FoV simulator. Furthermore, although not statistically significant, pilots reported a higher level of mental

workload in the restricted FoV simulator than in the wide FoV simulator. As discussed by Estock et al., the failure to find flight performance differences may be the result of the pilot's awareness that, in order to compensate for the reduced FoV, more attention was required to adequately perform the tasks. This claim is supported by the higher mental workload ratings in the narrow FoV condition.

The studies reviewed above show that pilots are able to compensate for small to moderate FoV restrictions without any measurable flight performance costs. One strategy to compensate for reduced FoV is to make larger and more frequent head movements to access important visual information. Gallimore, Brannon, and Patterson (1998) tested this compensatory strategy directly by examining pilot head movement at various angles of bank in three FoV conditions (40°, 60°, and 100°) using a F-15 flight simulator. Results indicated that pilots pitched their head significantly more at lower bank angles in the 40° condition than in the 100° FoV condition. Furthermore, head yaw movements were significantly different between each of the three FoV conditions with movements increasing as FoV decreased. As the authors note, frequent head movements may contribute to spatial disorientation (Gallimore et al., 1998). Gibbs et al. (1996) reported similar findings from an experiment that examined performance in a simulated F-18 target tracking and pursuit task. They found similar target pursuit performance between a restricted (40° FoV) and an unrestricted condition but increased head movements in the 40° condition. However, given the nature of the task (e.g., following), it is possible that pilots were able to keep the lead target in their central view most of the time, even in the restricted FoV condition.

A number of studies have investigated the effects of FoV restrictions on flight performance and head movements in the rotary-wing domain. Visual cues are important for determining aircraft orientation and position in many helicopter flight tasks. Thus, restricting the visual scene should have a large negative impact on the pilot's ability to precisely control the aircraft.

Similar to the effects of FoV restrictions on fixed-wing aircraft, the magnitude of the effect of restricted FoV in rotary-wing aircraft depends on the magnitude of the restriction, as well as on the nature of the task being performed. For example, in a study comparing two NVGs available for helicopter pilots, Jennings and Craig (2000) reported significant performance decrements in a hover task when using visual field-restricting NVGs compared to an unrestricted condition. Specifically, pilots had more difficulty maintaining lateral and longitudinal position in the restricted FoV conditions (40° and 52°) than in the unrestricted condition. However, there were no differences between the two restricted FoV conditions.

Jennings and Craig's (2000) results are consistent with other studies that examined the effects of restricted FoV on helicopter pilot performance. Specifically, results from a study by Szoboszlay, Haworth, Reynolds, and Lee (1995) showed that reduced FoV contributed to reduced control of the helicopter, increased workload, altered head movements, and reduced SA on a number flight tasks, including a hover, sidestep, pirouette, and slalom. In a follow-up study, Kasper, Haworth, Szoboszlay, King, and Halmos (1997) reported that pilot head movements and scanning patterns changed significantly when any FoV restrictions were imposed. In their study, horizontal FoV was restricted to 100°, 80°, 60°, 40°, and 20° and vertical FoV was restricted to 40°. Pilot

performance on the same tasks used by Szoboszlay et al. (1995) improved with increasing FoV until approximately 60°-80°, from which point no additional benefit of increasing FoV was observed.

Covelli, Rolland, Proctor, Kincaid, and Hancock (2010) examined the effect of FoV on helicopter pilot flight performance and head movements by manipulating both vertical and horizontal FoV. The pilot's task was to maintain runway alignment and vertical track in simulated helicopter base/final approaches. The visual display was a curved, rear-projection display screen with a field of regard of 170° (horizontal) x 75° (vertically). FoV was restricted based on a percentage of maximum unobstructed vision (i.e., 200° x 135°) using field-restricting glasses. The five restricted FoV conditions were 160° x 108° (80%), 120° x 81° (60%), 80° x 54° (40%), 40° x 27° (20%), and 20° x 13.5° (10%). Seven Bell 206 instructor pilots were recruited for the study. Each flight scenario was initialized at a base leg of a visual circuit pattern at an altitude of 600 feet above ground and an indicated airspeed of 85 knots. Pilots maneuvered to make coordinated turns to final, lining up with the runway to land at the runway intersection. Gaze, head movement data, and flight performance data were collected and analyzed.

The results of Covelli et al.'s study indicated that pilots adapted to FoV restrictions by changing their normal scan patterns. Covelli et al. argued that this adaptation occurred in order to gather relevant information to retain acceptable levels of SA. With respect to dwell (eye fixation) time, pilots tended to focus more on instruments than on the horizon during turns as FoV decreased. However, there were no significant differences in gaze dwell time in other aspects of flight. An overall trend was found for head movements where decreasing FoV resulted in an increase in range of head motion.

Specifically, the ranges of head movements were significantly greater when FoV was restricted below 40% (80° horizontal by 54° vertical). This effect was greatest in the turn phase from base to final. With respect to flight performance, runway alignment error increased significantly when FoV was restricted below 60% (120° horizontal by 81° vertical) and vertical track errors increased linearly as FoV decreased. The authors noted that, taken together, head movements, gaze, and flight performance are indirect metrics of workload and effort. However, they did not include direct measures of workload and SA in their methodology, making it difficult to assess the validity of this claim. Furthermore, the approach task used in this experiment does not involve many of the flying capabilities that are unique to rotary-wing aircraft, such as hovering or lateral flight. Given the importance of visual cues in these rotary-wing specific tasks, the effect of restricting FoV would be expected to have a more pronounced effect on flight performance.

The results of Covelli et al.'s (2010) study are consistent with the general findings in previously reviewed literature on FoV restrictions and flight performance. That is, flight performance is resilient to FoV restrictions up to a certain point, after which performance deficits become evident. Generally, flight performance decrements emerge at approximately 80° horizontal FoV. Second, restricting FoV forces pilots to modify their visual scan patterns and use greater and more frequent head movements, presumably to compensate for the loss of visual information that is available under non-restricted conditions. Finally, restricting FoV appears to increase pilot workload, perhaps due to the larger and more frequent head movements required under restricted FoV conditions.

The above research has all been conducted on pilots in complex and dynamic environments. Importantly, these dynamic environments have the potential to introduce

confounds that preclude making conclusions regarding the specific effect of FoV on performance. The following section will outline the literature on FoV restrictions for experiments conducted in more rigorously controlled laboratory conditions. In doing so, a clearer picture of the impact of restricted FoV on a number of basic cognitive tasks will highlight the need to examine the relationship between FoV and performance from a fundamental (theoretical) perspective.

Effects of Restricted Field of View on Performance

Fundamental research suggests that restricted FoV impairs the ability to move through one's environment, identify and track objects, judge distances, and construct accurate representations of one's environment in both real and virtual environments. The following sections review literature that has examined the association between FoV and human performance on these cognitive tasks.

Walking/Locomotion

Movement through one's environment is, in many cases, a visual task. One must locate and recognize objects, judge distances, and maintain spatial relations to avoid obstacles in order to safely and effectively maneuver through an environment. Navigating should therefore be easier with more visual information. Thus, restricting FoV may lead to substantial locomotion errors, which, depending on the application, may prove costly (e.g., soldiers performing nighttime military operations with NVGs). With this rationale, Toet, Jansen, and Delleman (2007; 2008) conducted a number of experiments to examine the effects of restricting FoV on maneuvering performance. They developed an obstacle course consisting of a narrow corridor with 'S' turns and various vertical obstacles. Participants wore safety glasses that were modified to manipulate horizontal FoV

(vertical FoV was held constant at 48°). Participants were required to move as quickly and as accurately (i.e., avoiding walls, ground objects, and elevated objects) as possible. A sensor was placed on participants' lower back to measure their position through the course. Toet et al. reported that restricting FoV caused participants to move more slowly through the course. Specifically, Toet et al. (2007) found that participants traversed the course significantly quicker in the unrestricted FoV condition than in all restricted FoV conditions (30°, 45°, 60°, and 75°), but with no significant completion time differences within the restricted conditions. Similar results were also obtained when the restricted FoV condition was extended to 120° (Toet et al., 2008).

Jansen, Toet, and Delleman (2010) examined the effects of vertical and horizontal FoV restrictions on maneuvering performance. Horizontal FoVs consisted of 40°, 80°, 115°, and 200° and were paired with vertical FoVs of 25°, 40°, 60°, 90° and 135°. Using Toet et al.'s (2007) obstacle course paradigm, Jansen et al. showed that restricting horizontal and vertical FoV increased the time to complete the obstacle course. Paired comparisons indicated that this difference was only significant between the smallest horizontal FoV (i.e., 40°) and all others. Similarly, the difference was only significant between the smallest vertical FoV (i.e., 25°) and all others. Thus, FoV only affected performance when it was reduced below a certain threshold. Until that point, the effects of FoV on locomotion performance were negligible. Neither horizontal nor vertical FoV manipulations affected accuracy of avoiding walls and objects. Head tracker data indicated that restrictions in horizontal FoV had no effect on yaw (side to side) head movements but vertical FoV restrictions contributed to an increase in pitch (up and down) head movements.

Toet and colleagues' results are consistent across their studies. In each study, restricting FoV resulted in increased the time to complete an obstacle course but did not affect accuracy. To explain these findings, the authors suggest that the loss of peripheral information most likely affected the maintenance of postural equilibrium, which resulted in decreased confidence and manifested itself in reduced maneuvering speed. Furthermore, they argued that by increasing head movements, participants were able to gather enough exteroceptive (visual information about the environment) and exproprioceptive (visual information of one's body relative to the environment) visual information to correctly judge the location of obstacles and control their foot placement. Alternatively, however, it may have been possible that participants sacrificed speed in order to maintain an acceptable level of accuracy, taking time to ensure accurate foot placement and obstacle avoidance. While research on locomotion is not directly applicable to flight performance *per se*, the finding that FoV affects the speed at which participants move through their environment should be analogous to the findings in the FoV and flight performance literature. For example, Kruk and Runnings (1984) reported that pilots with reduced FoV took longer to attain formation flight than pilots with full FoV. Thus, it is possible that pilots in the restricted FoV conditions took more time to establish their position in formation flight because a lack of confidence in the accuracy of their judgments.

Visual Search and Target Tracking

An observer's FoV when searching for or tracking objects may be important for a number of reasons. First, while peripheral vision may not be used directly in object identification, visual onsets in the periphery capture attention such that peripheral objects

can be foveated, attended to, and then identified. With a wide FoV, more objects in the periphery can be detected than with a narrow FoV. Furthermore, objects being tracked with a wide FoV are more likely to remain visible with less head movement than with a narrow FoV. This becomes particularly important when tracking objects with high velocities (Sandor & Leger, 1991). Research examining the effect of restricted FoV on search tasks indicates that search time increases as FoV decreases (Arthur, 2000; Venturino & Kunze, 1989; Wells, Venturino, & Osgood, 1988). In one of a series of experiments, Wells and Venturino (1990) examined the ability to track and monitor targets under various FoV ($20^{\circ} \times 20^{\circ}$, $45^{\circ} \times 42.5^{\circ}$, $60^{\circ} \times 50^{\circ}$, $90^{\circ} \times 60^{\circ}$, and $120^{\circ} \times 60^{\circ}$) and task complexity (3, 6, and 9 targets) conditions. Using an HMD, participants were required to locate targets, monitor them for change (i.e., become 'threats'), 'shoot' them down when they became threats, and indicate the positions of the targets after the simulation had been stopped. Results showed an interaction existed between FoV and task complexity. When only three threats were present, FoV did not affect performance. However, when six and nine targets were present, participants took longer to identify target changes and shoot down threats with narrower FoVs than with wider FoVs. Moreover, there were more head movements for narrow FoVs than for wide FoVs. According to Wells and Venturino, wider FoVs afforded the use of peripheral vision, which provided earlier cueing as to the location of the targets.

Arthur (2000) examined visual search in a virtual environment and found similar results to those reported by Wells and Venturino (1990). Using an HMD at three different FoV levels (48° , 112° , and 176°), participants searched a room for a target object. Search time was found to decrease significantly as FoV increased. These results suggest that

FoV affects participants' ability to acquire information about their surroundings. Peripheral cues capture attention such that stimuli in the periphery can be later identified. Furthermore, more spatial information must be mentally integrated to form a coherent mental representation of the environment under restricted FoV conditions (Wells & Kunze, 1989).

Distance Estimation

Operating under conditions that restrict FoV, such as when using NVGs or HMDs, may impair a pilot's ability to judge distances. Indeed, research has confirmed that restricting FoV causes significant underestimation of perceived distances (Loomis & Knaap, 2003; Niall, Reising, & Martin, 1999; Thompson et al., 2004; Whitmer & Kline, 1998). However, findings from distance perception research are inconsistent with respect to the effect of FoV reductions. For example, using a walking task paradigm, Fortenbaugh et al. (2007) reported that participants using an HMD perceived objects as being closer than they actually were. Participants explored a virtual environment to learn the locations of six statues. After being led back to a starting point and blanking out the positions of the virtual statues, participants were then asked to walk to the location where each statue was located. Fortenbaugh et al. found that the walking distances to the statues were significantly underestimated. Underestimations were explained as a consequence of the restricted FoV imposed by the HMD. Specifically, the restricted FoV effectively compressed the environment such that participants perceived it as being smaller than it actually was. In contrast to Fortenbaugh et al.'s findings, Arthur (2000) showed no differences of egocentric distance estimation in a virtual reality environment using HMDs at three different FoV restrictions (48°, 112°, 176°). One explanation for this discrepancy

is that distance underestimations using HMDs are due to the low display quality and not to FoV restrictions. Thus, if Arthur's HMDs produced better displays than Fortenbaugh's, then this could be the reason why Arthur did not find a difference.

Given the possible confound between FoV restrictions and display quality limitations (e.g., resolution, luminance, and contrast) associated with virtual environments, some researchers have attempted to isolate the effect of FoV on egocentric distance estimations in the real world by manipulating FoV using field-restricting glasses. However, as with the virtual environment studies, findings from real-world experiments have also been inconsistent. For example, Knapp and Loomis (2004) examined the effect of restricted FoV ($58^\circ \times 36^\circ$) on verbal distance estimations and visually directed walking tasks and found that distance judgments were just as accurate in the restricted FoV condition as they were in the unrestricted condition. However, Wu et al. (2004) reported that target distances were underestimated when FoV was reduced from 40° to 21.5° . One possible explanation for the disparate results in the real-world distance estimation literature is that the perceived compression of space only occurs under severe FoV restrictions (e.g., below 40°).

Creem-Regehr, Willemsen, Gooch, and Thompson (2005) used field-restricting glasses to examine the effect of restricted FoV and restricted head movements on distance perception. Participants were exposed to a full-FoV, a restricted FoV ($42^\circ \times 32^\circ$), and a restricted FoV/restricted head movement condition. After viewing the location of a 37 cm diameter foam disk that was placed on the ground, participants were blindfolded and were required to walk to the location of the disk. The foam disk was placed 2, 3.5, 5, 8, 10, or 12 meters from the participant and each distance was repeated

three times. Performance in the full-FoV condition and the restricted-FoV condition did not differ. However, walking distances in the restricted-FoV/restricted head movement condition were significantly less than in the other two conditions. The authors concluded that FoV restrictions alone do not contribute to the underestimation of distance and that head movements may provide additional environmental information that buffers the effect of restricted FoV when making distance estimations.

In summary, research examining the effects of restricted FoV on distance estimation shows that reduced FoV causes distance underestimations, particularly when restricted below 40°. Therefore, performance impairments on a helicopter hover task observed when field-restricting NVGs are used (Jennings & Craig, 2001) could be due to the pilot's inability to accurately judge distance from a fixed hover reference. Furthermore, impairments in attaining formation flight reported by Kruk and Runnings (1984) may have been a result of uncertainty regarding how far they were from the other aircraft while wearing the FoV narrowing HMDs. However, the negative effects of restricted FoV on distance estimation may be buffered by the freedom to move one's head. That is, head movements may afford the opportunity to attain the visual information necessary to build an accurate representation of one's environment, even under restricted FoV conditions. This may provide an explanation for why pilots adapt to restricted FoV conditions and preserve much of their ability to control their aircraft. However, the need for pilots to compensate for FoV conditions by making more head movements of greater magnitude may lead to additional problems, such as disorientation, head and neck strain, and mental workload.

Spatial Representations

Humans develop spatial knowledge of their surroundings by visually sampling features encountered when moving through their environment. Restricting FoV is thought to negatively affect construction of these spatial representations and interfere with the ability to form a comprehensive representation of one's environment by limiting the number of visual references to objects and landmarks. Field restricting devices (e.g., NVGs) adversely affect the acquisition of spatial knowledge of an environment. For example, Gauthier et al. (2008) examined the ability to actively navigate through and learn the layout of a life-size maze-like environment consisting of a number of rooms while wearing NVGs that restricted FoV to approximately 30°. A spatial memory test also examined the ability to acquire spatial knowledge about the environment. In the learning phase, participants were required to navigate through the environment in search of various objects that were located in the rooms. Participants were then given a spatial memory test that required them to judge the direction of a given object from a specific location in the maze and to draw the layout of the environment, including the location of the object from memory. The drawing task was used to assess memory for the spatial locations of the objects and not their identity. Therefore, participant scores were calculated as the number of correctly placed objects divided by the total number of objects in the drawing. Results indicated that participants in a no-NVG control condition were more accurate on relative direction judgments than those wearing NVGs, but only for targets in the same room. Furthermore, participants in the control condition placed significantly more objects in their correct locations than those wearing the FoV-restricting NVGs. Maps drawn by participants in the control condition also had better

‘goodness’ ratings than those drawn by participants in the NVG condition. Gauthier et al. suggest that factors associated with the use of NVGs (e.g., restricted FoV) could have contributed to gaps in the integration of visual scenes due to successive views. However, this study was not designed to assess the effects of FoV restrictions and therefore was not able to address this issue specifically.

Guterman et al. (2009) expanded on the findings of Gauthier et al. (2008) by specifically manipulating FoV and eliminating the confounds of the visual artifacts produced by NVGs (e.g., scintillating noise, halos, monochromatic imagery) by using field-restricting glasses. FoV was restricted to either 40° or 90°. Using Gauthier et al.’s (2008) paradigm, Guterman and colleagues measured distance and relative direction judgments, as well as map sketching and object placement to examine the effects of FoV on the construction of spatial representations. FoV was found to have no effect on distance and relative direction judgments or on the number of objects placed in their correct locations. However, FoV did affect the amount of distortion present in the sketched maps. Specifically, participants in the 40° FoV group drew more maps with incorrect numbers of rooms than those in the 90° FoV group. Moreover, maps drawn by the 90° FoV group were rated as significantly better than maps drawn by the 40° group in terms of both layout and geometry.

In sum, empirical findings from the distance estimation and FoV literature show that substantially restricting FoV and head movements causes the underestimation of distances of targets. This effect has been attributed to the difficulty of forming accurate mental representations of the environment when normal viewing conditions are prevented. The findings from Gauthier et al. (2008) and Guterman et al. (2009) supported

this explanation by showing that restricting FoV interfered with the creation of an accurate spatial representation of one's environment. Under restricted FoV conditions, multiple visual samplings of an environment are necessary to acquire sufficient information to create an accurate mental representation of the environment. However, in this process, some areas may be oversampled, while others may not be sampled at all. In some cases, when enough areas are undersampled, there may be insufficient information to create a coherent representation of the environment. Additionally, the cognitive mechanisms responsible for integrating these fragmented samples of the environment may be taxed to the point that they can no longer produce reliable and accurate outputs, particularly when the environment is complex and/or dynamic.

Summary

The literature reviewed above indicates that restricting FoV affects performance in both simple/complex and static/dynamic environments. With respect to pilots flying in complex and dynamic environments, research indicates that they make larger and more frequent head movements to obtain the necessary visual cues to maintain flight performance when FoV (peripheral information) is restricted. This finding has been replicated across different fundamental research paradigms. As noted in the review of distance estimation literature, making head movements to gain important visual information about one's environment buffers the effect of restricted FoV and preserves performance. However, increasing the magnitude and frequency of head movements may come with substantial costs (e.g., difficulty forming spatial representations), particularly in complex environments. Compared to unrestricted viewing conditions, FoV restrictions, coupled with increased head movements, appear to result in a fragmented internal

representation of the environment. Thus, one's cognitive system must somehow piece together these fragmented representations to create a unified percept so that appropriate judgments and decisions can be made. This cognitive integration may result in a substantial increase in overall workload. Working memory is responsible for holding, integrating, and making accessible visual information such that a complete and coherent representation of the environment can be perceived. Thus, FoV was hypothesized to directly affect the working memory system. The following section will introduce the construct of working memory and provide a more detailed theoretical link between FoV restrictions and the working memory system.

Working Memory

Working memory is a theoretical construct that refers to a short-term, limited-capacity system used in the processing and maintenance of information (Baddeley, 1986). Baddeley and Hitch's (1974) original working memory model was composed of an attentional controlling system and two slave systems: the *phonological loop* and the *visuo-spatial sketchpad*, which store and manipulate speech-based and visual information, respectively. The slave systems work in concert with the attentional control system, the *central executive*. Baddeley (2000) further refined the working memory model with the addition of the episodic buffer, which was proposed to integrate divergent information within the central executive. Baddeley's (2000) working memory model is shown in Figure 2.

Figure 2. Baddeley's (2000) Working Memory Model.

The Phonological Loop

The phonological loop is a working memory subsystem that, in part, stores verbal or speech-based information. It is comprised of two subcomponents; a phonological memory store and an articulatory rehearsal system. The rehearsal system relies on subvocal articulation to retain verbal information in working memory. Without rehearsal, verbal information would decay from working memory within two or three seconds (Baddeley, 1996). Auditory information is coded phonologically; however visual information can also be converted into a phonological code and stored verbally (Baddeley, 1990).

The phonological loop is the most extensively studied component of the working memory model and can account for many of the phonology-based effects reported in the literature (e.g., the phonological similarity effect, the word length effect, articulatory suppression). The phonological similarity effect refers to the finding that it is more difficult for people to recall a series of phonologically similar words (e.g., mat, cat, hat) than a series of phonologically dissimilar words (e.g., bat, hug, pen) (Conrad & Hull,

1964). Given Baddeley's assertion that the storage of information in working memory's phonological loop is based on a phonological code, and that recall requires discrimination between memory traces, then similar traces (i.e., phonological codes) will be more difficult to distinguish, and therefore more difficult to recall. The word length effect is that it is more difficult to recall a series of words that takes longer to read than a series of words that takes a shorter time to read (Cowan et al., 1992, Nairne, Neath, & Serra, 1997). Importantly, the word length effect is one of duration and not one of syllables, letters, and/or sounds (Baddeley, 1990).

The importance of subvocal rehearsal in preserving phonological information in working memory's phonological loop is highlighted in experiments that prevent rehearsal through articulatory suppression. A common articulatory suppression task is to utter a stream of irrelevant sounds (e.g., "baa, baa") or constantly repeat an irrelevant word (e.g., "the, the, the"). Articulatory suppression impairs the ability to recall visually presented stimuli and eliminates both the phonological similarity and word length effects (Baddeley et al., 1975). Thus, subvocal rehearsal is critical for storing and/or manipulating information in the phonological loop.

Research suggests that the phonological loop facilitates language development in young children and plays a crucial role in adult second-language learning (Baddeley, Gathercole, & Papagno, 1998). Researchers continue to investigate language development, solidifying the link between phonological working memory and language development (Warring, Eadie, Rickard Liow, & Dodd, 2016). Further, phonological working memory deficits have been linked to Specific Language Impairments (SLI;

Marini, Gentili, Moleni, & Fabbro, 2014; Torrens & Yague, 2016) and developmental language impairments in children (Henry & Botting, 2016).

The Visuo-spatial Sketchpad

The visuo-spatial subsystem, which stores and manipulates visual information, has received less attention than the phonological loop in the working memory literature. Initial evidence for separate visuo-spatial and phonological slave systems arose from the observation that some neuropsychologically impaired patients showed decrements in phonological performance (e.g., the digit span test) but showed no impairment in visuo-spatial tasks (e.g., the Corsi block tapping task). Other patients show the opposite pattern of decrements (i.e., impaired visual-spatial memory with preserved phonological memory), thus providing a double dissociation (e.g., DeRenzi & Nichelli, 1975, Della Sala & Logie, 2002).

The visuo-spatial subsystem consists of a short-term memory system and is capable of manipulating visual imagery and integrating visual-spatial information from long-term memory (Baddeley, 2007). The visuo-spatial sketchpad consists of two sub-components: the *visual cache* and the *inner scribe* (Logie, 1995). Somewhat analogous to the storage system in the phonological loop, the visual cache acts as a short-term store for visual information (e.g., shape, colour), while the inner scribe is an active rehearsal component that is responsible for planning and executing physical movement, and for maintaining information in the visual cache.

The visuo-spatial subsystem plays an important role in spatial reasoning (Vandierendonck & De Vooght, 1997), navigating (Garden, Cornoldi, & Logie, 2002), and playing chess (Robbins et al., 1996). A more recent study by Johannsdottir and

Herdman (2010) showed that visuo-spatial working memory is also important in the real-world application of maintaining lane position and SA for other vehicles while driving.

The Central Executive

The least understood component of Baddeley's working memory model is the central executive. In fact, Baddeley himself admits to having avoided explicit investigation of the executive and focused instead on the more tractable investigations of the two slave systems. That said, the central executive is posited to be an attention-limited supervisory system that controls the two slave systems. Early descriptions of the central executive have likened it essentially to a homunculus: "a little man in the head who takes all the important but difficult decisions" (Baddeley, 2007, p. 118). Despite the infinite regress problem of the homunculus (i.e., a homunculus to control the homunculus), progress is being made to refine the concept and functionality of the central executive.

While the central executive has been argued to be important in most cognitive tasks (e.g., Kane, Bleckley, Conway, & Engle, 2001), Baddeley (2007) hypothesized that the central executive is critical in focusing, dividing, and switching attention, and in linking working memory to long-term memory (Repovs & Baddeley, 2006). Furthermore, Baddeley (1998) has argued against the idea of the central executive being isolated to a specific neuroanatomical location in the brain. Neuropsychological research has corroborated this claim by showing that a number of brain regions are involved in central executive functioning, including the prefrontal cortex, the left parietal and cerebellar regions, as well as the occipital, temporal, and subcortical areas (D'Esposito et al., 1995; Garavan, Ross, Li, & Stein, 2000). Thus, it is likely that these brain regions

work in concert to support executive function. As noted by these authors, the isolation of brain regions that are exclusively involved in executive functioning is difficult given that central executive tasks are likely to activate the other working memory subsystems.

As with experiments on the phonological loop and visuo-spatial sketchpad, central executive functioning is often examined using a dual-task paradigm. Random number generation or random tapping tasks are typically used as the secondary ‘load’ tasks when assessing central executive function. In these secondary tasks, participants are required to generate random sequences of numbers or press keys on a keypad in a random pattern. The assumption is that participants must actively monitor their responses so as not to produce non-random patterns in their responses. Support for the claim that random generation taxes the central executive comes from studies examining Alzheimer’s patients and patients with frontal lobe lesions who display difficulty generating random sequences (Brugger, Monsch, Salmon, & Butters, 1996) and who have difficulty performing two concurrent tasks (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986), both of which indicate impairments in the ability to coordinate attentional resources; a function of the central executive (Baddeley, 1996). Research has also linked impairments of central executive functioning to disorders such as attention deficit/hyperactivity disorder (Alderson, Hudec, Patros, & Kasper, 2013) and obsessive-compulsive disorder (Martoni, Salgari, Galimberi, Cavallini, & O’Neill, 2015) in adults, as patients suffering from these disorders displayed a noted lack of executive organization strategies and self-regulation (Hoffman, Schmeichel, & Baddeley, 2012).

The Episodic Buffer

The episodic buffer was proposed by Baddeley (2000) to address the criticism that working memory's information capacity exceeded that of the verbal and visuo-spatial slave systems. There was also need for a mechanism that allowed the verbal and visuo-spatial systems to interact with each other and with long-term memory (Baddeley, 2007). The episodic buffer is conceptualized as a limited capacity storage system controlled by the central executive, which functions to integrate or bind information into episodes or chunks. The central executive retrieves information from the episodic buffer. This amalgamation of information is what we experience as conscious awareness (Baddeley, 2000). Furthermore, the central executive is hypothesized to be able to manipulate the content of the episodic buffer by focusing attention (e.g., visual, auditory) or by drawing episodic and semantic information from long-term memory.

Evidence for the episodic buffer comes from observations of amnesiac patients with little-to-no long-term memory, but who retain the ability for immediate prose recall (Baddeley & Wilson, 2002). Baddeley and Wilson described a patient who, despite severely compromised long-term memory, was able to recall passages of prose of up to 25 idea units, which is far beyond the capacity of the phonological loop and visuo-spatial sketchpad. As noted by Baddeley and Wilson, prose recall requires access to semantic representations in long-term memory and the binding of information from long-term memory with a working memory representation. Given that the patients' long-term memory was compromised, the binding of information was inferred to be occurring in working memory, a process mediated by the episodic buffer.

In response to findings since its initial proposal, Baddeley (2012) has questioned the ability of the episodic buffer to actively manipulate information. In a series of experiments examining the binding of form and colour, Baddeley, Allen, and Hitch (2011) found that, when paired with a backward counting task, binding visual stimuli (e.g., colored shapes) required no more attention than binding these features across modal stimuli (one feature was visual, another auditory). This research was consistent with previous binding research by the authors (Allen, Baddeley, & Hitch, 2006), which also suggested that binding was not an attentionally demanding task. As such, Baddeley has revised his original notion of the buffer, now envisaging it as a passive store for multi-dimensional information.

Field of View Restrictions and Working Memory

FoV restrictions and their effects on human performance in applied settings, as well as the function of working memory and its subsystems, have both been widely studied, albeit independently. To date, no studies have systematically examined the link between FoV restrictions and working memory. That is, in addition to restricting visual information in our periphery, FoV restrictions may have a substantial effect on our cognitive system's ability to form cohesive representations of visual environments (e.g., working memory). As noted earlier, in order to compensate for FoV restrictions, the observer must repeatedly sample the environment to effectively interact with it. In doing so, some visual samples will overlap, while other areas of the environment remain completely unsampled. Interestingly, the human observer is able to effectively interact with the environment and maintain acceptable levels of performance despite challenges to the visual and perceptual systems (e.g., restricted FoV using NVGs). It is therefore

apparent that under sub-optimal viewing conditions, the human cognitive system is capable of effectively piecing together fragmented samples of the environment. However, under certain circumstances, this cognitive system appears to break down. This is evidenced by performance deficits caused by FoV restrictions in a number of everyday activities, such as walking (Toet et al., 2008), searching (Wells & Venturino, 1991), and building spatial representations of our environments (Gauthier et al., 2008; Guterman et al., 2009). These performance deficits are hypothesized here to be attributable to overloading working memory to the extent that complete and/or coherent mental representations can no longer be formed.

Ongoing development and maintenance of complex visual and spatial representations (e.g., in the flight environment) are believed to heavily tax the visuo-spatial working memory system. Consequently, any further strain on the visuo-spatial system, such as those caused by a restriction to the visual field, could overload working memory and produce performance impairments. For example, objects or events in a pilot's peripheral visual field could go unnoticed if, when using NVGs, the area of the environment is not sampled via head movements. Thus, pilots must continually scan the environment to maintain SA and to ensure that objects/events are not missed simply due to the physical restriction of their FoV. Given these additional head movements, visuo-spatial working memory must retain more information about the peripheral field given that it is no longer visually accessible. Moreover, the visuo-spatial memory system must develop and maintain a representation of the environment, a task that may be difficult given the increase in visual sampling rate and the integration required to amalgamate numerous visual fragmentations caused by FoV restrictions. Thus, demands on visuo-

spatial working memory should be expected to increase as FoV decreases. The finding that performance impairments are only observed when the FoV is restricted beyond a certain threshold (e.g., Kasper et al., 1997; Szoboszlay et al., 1995) may reflect a breaking point (i.e., limit) in visuo-spatial working memory. That is, the visuo-spatial system can cope with the added processing costs of restricting FoV, but only up to a certain point, after which it becomes overloaded and memory begins to fail.

Baddeley (1990) indicated that the phonological loop is able to transform visual information into phonological code. There is further evidence that the phonological system, specifically the articulatory loop, may play a role in executive functions. For example, Emerson and Miyake (2003) conducted a series of experiments to investigate the role of the phonological loop in the executive function of task switching. They proposed that sub-vocal articulation is utilized as a sort of control mechanism when switching between two tasks. In their study, participants switched between addition and subtraction tasks while simultaneously performing a benign secondary foot-tapping task, an articulatory suppression task (repeating “a, b, c”), or no secondary task (control condition). Results indicated that the articulatory suppression condition resulted in significantly greater switch costs (time per operation switch) than the foot tapping or control conditions, which did not differ from each other. This finding supports the claim that sub-vocal articulation aided the executive control system as an internal self-cueing mechanism that provided a phonological cue for switching to the next arithmetic operation.

Johannsdottir and Herdman (2010) also provided evidence that the phonological loop is able to support non-verbal tasks in their examination of the relationship between

working memory and SA in a dynamic driving task. They showed that SA for the location of other vehicles in the driving environment was differentially affected by taxing working memory's visuo-spatial and verbal subsystems. In their experiment, the visuo-spatial system was taxed by auditorally providing participants with two clock times (e.g., "4:00" and "9:00") and asking them to decide whether the angle formed between the minute and hour hands on an analogue clock was the same or different. The verbal subsystem was taxed by having participants indicate whether a series of auditorally presented word pairs shared a sound (e.g., "computer and pewter", "busy and cucumber"). The results showed that loading the visuo-spatial subsystem (clock task) impaired the participants' SA for the location of vehicles in front of them whereas loading the verbal subsystem (word task) impaired their SA for the location of vehicles behind them. They concluded that the visuo-spatial working memory is responsible for maintaining visual information that is readily available (i.e., in view) whereas phonological working memory maintains a representation of information that is not in immediate view (e.g., vehicles behind the driver).

Given the fractionation of working memory (i.e., separate subsystems for verbal and visual information), Johannsdottir and Herdman expected that judgments of position and distance would primarily involve the visuo-spatial subsystem. However, their findings showed that the verbal subsystem assisted the visuo-spatial system when visual information was not easily accessible. The authors further noted that the verbal subsystem might have also assisted the executive system through the use of verbal cues (vocal or subvocal) to remind themselves to check their rear-view mirrors so that the position of vehicles behind them can be updated. This claim is consistent with Emerson

and Miyake's (2003) assertion that the verbal subsystem can adopt executive functionality (e.g., task switching). Thus, it is possible that in the event of a severe load on the visuo-spatial and central executive systems (e.g., those produced by large FoV restrictions) the phonological system is recruited to assist by coding visual stimuli phonologically and/or by allocating attention in certain situations. The present thesis examined this possibility.

In addition to increasing the workload of phonological and visuo-spatial working memory, FoV restrictions are likely to also increase the workload of the central executive. As the supervisory system responsible for allocating resources within working memory, increased strain on both phonological and visuo-spatial components due to restricted FoV may require more efficient coordination of these resources. Moreover, with increased visual sampling rates and expected increased strain on the visuo-spatial system, integration of visual information is required to piece together visual samplings in order for the cognitive system to create a comprehensive percept. While this integration of visual and verbal information was originally proposed to take place within the episodic buffer (Baddeley, 2000; but see Baddeley, 2012), the allocation of attention from the subsystems or from LTM is assumed to be controlled by the central executive. As such, increases in these demands should result in greater workload and strain on the central executive.

While little is known about the episodic buffer, it is proposed to store multi-dimensional information and provide access to information within long-term memory (LTM). If FoV affects only visuo-spatial working memory, it could be expected to do so in isolation, not requiring support from additional working memory components.

However, given the potential role of both verbal and visuo-spatial subsystems in processing visual information, the episodic buffer may be particularly important in providing a comprehensive picture of one's environment. If the assumption that phonological working memory is recruited to assist visuo-spatial working memory when this system is heavily taxed (i.e., under restricted FoV conditions) is correct, it would be imperative to have a structure to make this information available. However, as with the phonological and visuo-spatial stores, the episodic buffer has a limited capacity. As such, this component, too, is likely to be overwhelmed with significant FoV restrictions.

Present Research

The objective of the present research was to examine the effects of FoV restrictions on working memory. Three experiments were conducted. The experimental sequence is depicted in Figure 3. Experiment 1 examined the impact of restricting FoV on a geon memory task (GMT). Experiment 2 explored the relative difficulty of working memory tasks used in Experiment 3. Experiment 3 examined the effect of FoV on working memory. In addition to identifying which working memory components (e.g., phonological, visuo-spatial, central executive) were affected by FoV, Experiment 3 explored the learning rates associated with restricted FoV conditions.

Figure 3. Experimental layout and associated goals. Geon memory task (GMT) is the primary task used in Experiments 1 and 3 and was developed for the present research.

CHAPTER 2: EXPERIMENT 1

The goal of Experiment 1 was to assess the effects of restricted FoV on a task involving memory for geon identities and locations. Previous research has used similar tasks to the GMT proposed here as an index of spatial memory. For example, Arthur (2000) examined the effect of FoV on spatial memory using HMDs where participants recalled the spatial arrangements of different colored circles positioned on the floor of a maze, but did not find an effect of FoV. One possible reason for this null effect was that participants only had to recall the location of five circles, making the task quite easy (i.e., ceiling effect). Moreover, the circles were placed on the floor of a narrow corridor in a small maze, substantially limiting the locations in which they could be placed: The mean distance error across all FoV conditions was approximately only 15 centimeters. Using a larger, more realistic environment with more objects to be remembered may produce enough variability in responses to produce a FoV effect.

The present experiment used a virtual environment populated with three-dimensional geons¹. Participants were required to view this environment under two different FoV conditions. Once the geons were removed, participants were asked to recreate the virtual environment from memory as best as they could by replacing the appropriate geons to their correct locations.

It was expected that participants completing the GMT under restricted FoV conditions would perform worse than when completing the same task under wide FoV

¹ Geons, short for *geometrical ions*, are two or three-dimensional forms (e.g., cones, circles, pyramids, cylinders, squares, etc.) theorized to form the basis of more complex structures (Biederman, 1987).

conditions. Participants may use the layout of geons within that environment and their spatial relationships to each other to assist in the reconstruction from memory. When exploring an environment using a wide FoV, participants may have a better “big picture” representation of the environment, including being able to see more geons and their locations relative to one another at a single time, effectively minimizing the demand on working memory. Alternatively, when viewing environments with a restricted FoV, participants may be required to sample various small portions of the environment, requiring them to maintain a greater amount of visual information in working memory to develop a coherent understanding of the layout. Further, the cognitive effort required to maintain this additional visual information may exceed the limits of working memory, thereby impeding participants’ ability to remember the identity of the geons.

Method

Participants

A total of 41 Carleton University undergraduate participants (27 female; 14 male) were recruited for this experiment using SONA. Their ages ranged from 17 to 31 ($M = 19.6$, $SD = 2.65$). Participants were compensated with course credit. Only 30 participants were able to complete the experiment in the allotted time and only their data are included in subsequent analyses. Participants had normal or corrected-to normal vision but could not wear glasses that prohibited them from wearing the field-restricting glasses.

Stimuli and Apparatus

The GMT was displayed on the Advanced Cognitive Engineering (ACE) Lab’s Broad Angle Display System (BADs) (see Figure 4). The display combines eight 1920 x 1080 high definition projectors which displays a seamless, high-resolution image onto a

curved screen with a FoV of 180° (horizontal) x 47° (vertical) and spans 20' 8" in length and 10' 9" in height. This display was chosen because of the wide FoV available to participants and the sense of immersion it created. Participants sat on a platform located directly in the center of the display for the duration of the experiment. FoV was manipulated using two pairs of field-restricting glasses. Safety glasses were modified to create FoVs of approximately 40° and approximately 120° (Figure 5).

Figure 4. Broad angle display system (BADS).

Figure 5. Modified safety glasses to produce (a) 40° FoV and (b) 120° FoV

Geon Memory Task

A GMT was developed as a visual and spatial memory task and was used in Experiments 1 and 3. The premise of this task was to view a virtual scene and remember the identity and location of eight three-dimensional geons. After a viewing the geon-populated scene for a 30-second learning phase, participants were required to reproduce the virtual scene by placing the correct geons back to their correct locations.

The virtual environment used in the GMT was created using the Unity gaming software. A portion of a scene is shown in Figure 6. The environment consisted of flat rectangular clearing surrounded by long grasses, shrubs, and large trees. The topography included a number of rolling hills. There were three relatively small red-leaved trees, equally spaced along the far end of the clearing and a gazebo and bench situated in one of the far corners of the clearing. These familiar items were included to help participants scale the size of the clearing. The geons used in the task were simple, three dimensional geons (cube, rectangle, prism, arch, cone, etc.). These geons were created in either Unity or imported from Blender, a 3D modeling software. Shadows were placed beneath the geons to provide additional size and distance cues. All geons were positioned the same height above the ground, however, given that some were placed closer to the viewers eye-

point than others, they varied in their vertical placement on the display. Geons were also dispersed horizontally such that they were not concentrated in any one quadrant of the virtual clearing. Multiple geons were in view at any given fixation when viewing the scene in the narrow FoV condition. In total, 30 unique shape and colour combinations of geons were developed. Four scenes, each consisting of eight geons, were created. Thus, two geons were used twice in two of the scenes.

Figure 6. Virtual environment with 3D geons

The GMT was divided into two distinct phases: learning and replacement. The learning phase was 30 seconds in duration. After reviewing instructions of the task, participants were asked via the response interface whether they were ready to begin. The response interface was a PC located directly beside participants with presentation via a 20-inch Samsung computer monitor. Immediately upon clicking the text box on the screen in confirmation, the virtual scene loaded and was presented on the display system.

The environment, along with the eight geons, was presented for the 30-second duration. During this time participants explored the environment with the goal of memorizing the identities of the geons and their locations. After 30 seconds, the screen flickered and the geons disappeared. The background environment remained visible.

The replacement phase began as soon as the geons disappeared. At the time the geons disappeared, a top-down view of the environment, along with 12 geons, appeared on the response interface screen. The 12 geons consisted of the eight original geons that were presented, along with four foils. Participants were required to select the original eight geons and, using the drag and drop method via a computer mouse, place each geon into its original position in the environment. In addition to using the top-down view provided by the response interface, participants were able to view their responses in real time with the original point of view on the display, thus retaining the initial perspective of the environment. When finished, they were instructed to click a 'Done' tab on the screen to submit their responses. While no feedback was given to the nature of errors of individual geons, participants were given immediate feedback as to whether the scene was correct or incorrect. Thus, if an error was made, participants did not know which geon was correctly selected and placed. A geon was deemed correct if it was placed within a predefined circle (e.g., 22 feet) of the original geon location. Participants repeated the learning and replacement phases of a scene (i.e., geon locations were identical within a scene) until they successfully replaced all geons on two consecutive trials. This caveat was included to guard against guessing. There was no time limit on the replacement phase of the task; however, time was recorded. Once correct placements were made for all geons on two consecutive trials, the procedure was repeated for the

second virtual scene. Participants then repeated this procedure for a total of four scenes (i.e., two virtual scenes) for the alternate FoV condition.

Design and Procedure

Experiment 1 used a one-factor (FoV: 120°, 40°), within-subjects design. FoV was blocked with order counterbalanced across participants. Prior to the experimental trials, participants were briefed as to the nature of the experiment and signed an informed consent form. The GMT was then explained and participants completed a practice trial to ensure that the task was understood and they were familiar with the response interface, including getting used to moving geons from the response interface to the display screen. Participants completed the GMT for a total of four scenes, two for each FoV condition.

Measures

Performance on the GMT was evaluated based on four measures. Measures 1 and 2 were measures of general performance as they required both correct geon selection and accurate replacement. Measure 3 was specific to visual memory (i.e., geon identity), while Measure 4 was specific to spatial memory (i.e., geon location).

1. Number of attempts to recreate the scene. The number of trial repetitions to successfully recreate the scene on two *consecutive* attempts.
2. Proportion of geons replaced incorrectly. The proportion of incorrect placements (i.e., incorrect geon selection *and* geon placement from the total number of geons placements. Incorrect placements were calculated instead of correct placements to maintain continuity such that higher scores reflect poorer performance.
3. Geon Selection Accuracy: The proportion of distractor geons selected, regardless of whether they were replaced in the correct location, out of the total number of

geon selections made was calculated to assess geon identity memory. The proportion of incorrect selections was assessed instead of the proportion of correct selections to maintain continuity such that higher scores on this measure reflected poorer performance.

4. Geon Placement Accuracy: A measure of spatial memory. The accuracy of replacement locations, averaged across all geons in that trial, calculated as the root mean square error (RMSE) of geon placement locations in feet (i.e., the difference between the actual and indicated geon locations with directionality removed). RMSE was calculated by squaring all of the geon placement error scores in the data set, calculating the mean of those squared errors, and then calculating the square root of the mean of the squared errors.

Results

Prior to analyses, each dependent variable was checked for outliers, missing data, normality, and homogeneity of variance. Unless otherwise specified, data complied with all assumptions. Dependent measures were considered mutually exclusive in that if a participant was an outlier on one measure, they were not automatically removed from all analyses. As such, the degrees of freedom from the following analyses may vary from one dependent measure to the next. Paired samples *t*-tests were conducted between 40° and 120° FoV conditions for each dependent variable.

Number of Attempts to Recreate the Scene

As shown in Figure 7a, participants required a significantly greater number of attempts to successfully recreate the scene in the 40° FoV condition ($M = 5.5$, $SD = 1.51$) than in the 120° FoV condition ($M = 4.8$, $SD = 1.44$), $t(27) = 2.358$, $p = .026$, $d = .45$.

Proportion of Geons Replaced Incorrectly

As shown in Figure 7b, participants replaced more geons incorrectly in the 40° FoV condition ($M = .20$, $SD = .056$) than in the 120° FoV condition ($M = .17$, $SD = .048$), $t(27) = .2731$, $p = .011$, $d = .52$.

Geon Selection Accuracy

To isolate whether FoV affected memory for the geons independent of spatial location, the number of times a distractor geon was selected was recorded for each attempt. A paired-sample t -test revealed no difference between the proportion of distracter geons selected in the 40° ($M = .0274$, $SD = .021$) and 120° ($M = .0303$, $SD = .022$) FoV conditions, $t(28) = -0.564$, $p = .577$. Thus, based on this analysis, memory for geons identity is not affected by FoV.

Geon Replacement Accuracy

Total placement errors were significantly greater in the 40° FoV condition ($M = 18.09$, $SD = 4.15$) than in the 120° FoV condition ($M = 16.35$, $SD = 3.61$), $t(28) = 2.10$, $p = .045$, $d = .39$. Mean geon placement errors by FoV condition are presented in Figure 7c.

Given the possibility that the total placement errors (i.e., averaged over all attempts) could considerably underestimate the effect of FoV restrictions, the average placement errors were also calculated for the first three trials only. Underestimation of the FoV effect for total placement errors was thought possible because as the number of attempts for each participant increased, the magnitude of the errors decreased. In situations where participants were close to completing the task (e.g., having difficulty with only one geon), the magnitude of the placement errors would be small, thereby bringing down the average. The current analysis was limited to the first three trials

Figure 7. Bar graphs depicting significant differences between wide and narrow FoV conditions for (a) number of attempts required to recreate the scene; (b) proportion of geons replaced incorrectly; (c) geon placement errors for all attempts; and (d) geon placement errors for first three attempts. Error bars represent standard error.

because the mean number of trials required to complete the experimental task for the entire sample was approximately five. Given that the last two trials would have minimal errors (as geons would have all been within the ‘correct’ threshold distance), the first three attempts would produce the most informative measure of the initial FoV effect, while at the same time providing sufficient data points to make the analysis meaningful. As depicted in Figure 7d, consistent with the total placement errors, participants made significantly greater placement errors in the 40° FoV condition ($M = 26.65$, $SD = 10.25$) than in the 120° FoV condition ($M = 22.45$, $SD = 9.08$), $t(28) = 2.356$, $p = .026$, $d = .44$.

Discussion

Experiment 1 showed that restricting FoV impaired performance on the GMT. More importantly, however, this experiment revealed that FoV reductions impaired performance on the spatial memory component (i.e., remembering locations), but not the geon identity memory component of the GMT. Specifically, restricting FoV increased the number of attempts required to complete the GMT, decreased the proportion of geons replaced correctly, and impaired geon placement accuracy resulting in larger geon placement errors. FoV did not affect memory for geon identity.

Given that geon identification is a visual task, the current findings support a distinction within the visuo-spatial working memory system. Logie and Pearson (1997) found evidence for the fractionation of the visio-spatial system, where the visual information is stored through the visual cache and spatial components are stored through the inner scribe. That geon identification appears unaffected by FoV suggests that visual and spatial information are processed and held by separate but closely related systems.

CHAPTER 3: EXPERIMENT 2

Experiment 1 was important in establishing that the size of the FoV affects performance, but was not designed to investigate specifically how FoV affects basic cognitive performance. The next step in the current thesis was to include a manipulation of working memory and examine how FoV, working memory, and performance relate to one another. However, prior to examining the FoV/working memory relationship, it was important to ensure that manipulations and stimuli using the GMT were appropriate. As such, Experiment 2 follows with an examination of the working memory tasks used with a dual-task paradigm described below.

The purpose of Experiment 2 was to examine whether the tasks designed to tax phonological, visuo-spatial, or central executive working memory in Experiment 3 were of comparable difficulty. The dual-task paradigm used in Experiment 3 required participants to complete two tasks simultaneously. Performance during the dual-task condition was compared to baseline performance in single-task conditions. The logic behind this paradigm is that when two tasks utilize the same cognitive resource (e.g., phonological working memory), performance on one or both tasks will be poorer than if they do not use the same cognitive resource, above and beyond the negative effects of performing two tasks concurrently. Given that performance on the primary task is assumed to be affected negatively if the two tasks require the same cognitive resource, it is important to evaluate the relative difficulty of the secondary tasks. If overlooked, performance differences on the primary task could be attributable to differences in the level of difficulty of the working memory tasks as opposed to a sharing of limited cognitive resources.

A Perceptual Detection Task (PDT) was used to assess the difficulty of the working memory tasks. The auditory PDT is a simple reaction time task where participants indicate by the press of a button when they hear an auditory tone. To assess workload, the PDT is performed concurrently with another task. Primary tasks that are more cognitively demanding are assumed to produce greater response latencies and more misses than tasks that are less cognitively demanding. The PDT has been used previously as a measure of workload (Chong, Mirchi, Silva, & Strybel, 2014; Van der Horst & Martens, 2010; Olsson & Burns, 2000; Patton, Kircher, Ostlund, Lilsson, & Svenson, 2006), including investigations of cognitive tunneling (e.g., Martens & Van Winsum, 2000).

The present study compared the cognitive difficulty of the three common working memory tasks to be used in Experiment 3: counting (phonological), spatial tapping (visuo-spatial), and random tapping (central executive). It also included a counting and tapping condition to examine whether the action of simply pressing a button could contribute to an increase in workload and cognitive resources. The counting task is similar to other tasks that have been used in the literature to utilize phonological resources (e.g., reciting months of the year, days of the week, generic articulatory suppression tasks). The spatial tapping and random tapping (or random generation) tasks have both been used extensively in previous research (e.g., Curci, Lanciano, Soleti, & Rime, 2013; Meneghetti, De Beni, Gyselinck, & Pazzaglia, 2013; Otsuka & Osaka, 2015; Yang, Gathercole, & Allen, 2014). The present experiment will compare the difficulty of each task by examining the response latencies to an auditory PDT.

Counting is a simple task and, as such, was expected to produce the shortest response latencies (i.e., least workload) to the auditory PDT. Moreover, the addition of a single key pressing motion for each number counted was not expected to contribute significant additional workload. However, the spatial tapping and random tapping are generally identified as more difficult tasks, and as such, were expected to produce the longest response latencies.

Method

Participants

Thirty-three undergraduate students (22 females; 11 males) participated in the experiment and were recruited via Carleton University's SONA system. Participants were offered course credit in exchange for their participation.

Stimuli and Apparatus

The experimental stimuli were presented on a Dell PC and Samsung 21-inch monitor. Responses to the working memory tasks and PDT responses were recorded using a seven-button keypad (see Figure 8) that was connected to the Dell PC. The keypad consisted of four white keys, a green key, a blue key and a red key and recorded individual keystrokes and associated response times. Button presses were recorded for all tasks. Voice recordings were made for the counting tasks.

Figure 8. Working memory and PDT response keypad.

Experimental Design and Procedure

The present study was a one-way, within subjects design. After reviewing the instructions with the investigator, participants first completed five 30-second trials of baseline PDT testing, each consisting of seven exposures to the auditory tone.

Presentation of the tone occurred randomly at between 2-6 second intervals. Participants then completed the four experimental tasks. The order of these tasks was counterbalanced using a Latin square design. As in the baseline condition, participants completed five trials of each experimental task. Each trial was approximately 30 seconds in duration and the auditory tone was presented at random intervals of 2-6 seconds.

Instructions for each experimental task were as follows:

- *Counting.* Count out loud for the duration of the trial. Ensure you count out loud as your voice will be recorded. Count at a consistent, medium-paced tempo for the duration of the trial, approximately 1 per second.
- *Counting and Tapping.* Count out loud for the duration of the trial. At each moment you say a number, press the blue button on the keypad with your left hand. Counting and pressing must occur in unison. Count at a consistent, medium-paced tempo for the duration of the trial, approximately 1 per second. Voice and key presses will be recorded.
- *Spatial Tapping.* Using your left hand, continually press the four-key pattern of white keys in the order indicated by the image below (see Figure 9). Repeat this pattern as accurately as possible for the duration of the trial. Ensure key presses are at a consistent, medium-paced tempo, approximately one per second. Key presses will be recorded.

Figure 9. Key pressing sequence for the spatial tapping task.

- *Random Tapping.* Using your left hand and only the four white keys, generate a random sample of key presses. Make special effort to ensure that key presses are completely random and unpredictable, and that you create no noticeable patterns. Ensure key presses are at a consistent, medium-paced tempo, approximately one per second. Key presses will be recorded.

Results

Prior to statistical analyses, the data was screened for missing data and outliers. A total of 42 (0.7%) PDT tones were missed (2 in the baseline, 2 in the counting, 3 in the counting/tapping, 10 in the spatial tapping, and 25 in the random tapping conditions). In addition to removal of 107 (1.8%) PDT reaction time outliers (> 3 SDs from the mean of the respective working memory task), PDT reaction times below 200 ms were judged as anticipatory and removed. In total, 98 (1.7%) PDT reaction times below 200 ms were removed. Data analyses were conducted on the remaining 5, 528 PDT reaction times. Unless otherwise specified, data complied with all assumptions.

PDT Responses

A one-way, repeated measures ANOVA was conducted on PDT reaction times for each working memory task. Mauchly's test of sphericity indicated that the assumption of sphericity was violated, $\chi^2(9) = 56.778, p < .001$, therefore degrees of freedom were

corrected using the Greenhouse-Geisser estimate of sphericity ($\epsilon = .497$). The overall ANOVA was significant, $F(1.99, 63.65) = 93.37, p < .001, \eta_p^2 = .745$, indicating differences in reaction times to the PDT between working memory tasks. Mean reaction times, along with 95% confidence intervals are provided in Figure 10.

Figure 10. Mean PDT reaction times by working memory task. Error bars represent 95% CIs (Loftus & Mason, 1994).

As depicted in Figure 10, baseline PDT responses were quicker than responses with a concurrent working memory task. The simple counting task produced response latencies significantly greater than those of the baseline latencies. The addition of a motor component (i.e., key tapping) to the counting task caused significantly greater reaction times than counting alone. The addition of a spatial component (spatial tapping) further increased reaction times significantly. Finally, random tapping, designed to load the central executive component of working memory, produced the greatest response latencies.

Working Memory Tasks

Performance on the working memory tasks was also examined. Counting and counting/tapping tasks were voice recorded and key presses were recorded for the counting/tapping, spatial tapping and random tapping tasks. These data were examined for number and rates of responses. Spatial tapping was examined for correctness of response sequences and random tapping was assessed for randomness of responses.

Each experimental trial was 30 seconds long and participants were instructed to count or press keys at a rate of approximately one key per second. However, they were also told not to make the rate of key presses their focus so much so that it distracted them from the PDT or the accuracy of their responses. As shown in Figure 11, the rate of counting in the counting and counting/tapping conditions approximated the requested rate of one per second ($M = 32$, $SD = 7$ and $M = 40$, $SD = 10$ counts/key presses per 30-second trial for the counting and counting/tapping tasks, respectively). However, number of key presses for spatial and random tapping tasks was approximately double the rate of the counting and counting tapping tasks with 70 ($SD = 17$) and 66 ($SD = 20$) per 30-second trial, respectively. A one-factor, repeated measures ANOVA (with Greenhouse-Geisser correction for a violation of sphericity) indicated that the rate of key pressing differed significantly across groups, $F(1.98, 55.55) = 81.685$, $p < .001$, $\eta_p^2 = .745$. Examination of 95% CIs indicated that response rates in the spatial and random tapping tasks were greater than those of the counting and counting/tapping tasks.

Figure 11. Mean response rate per 30-second trial by secondary tasks. Spatial and random tapping tasks had significantly greater generation rates than counting and counting/tapping. Counting/Tapping rates were significantly greater than counting alone. Error bars represent relational 95% CIs (Loftus & Mason, 1994).

Working memory task performance was assessed for the counting and counting/tapping tasks by simply ensuring that these tasks were being carried out. In all cases, participants were able to successfully carry out the counting and counting/tapping tasks. Performance on the spatial tapping task was assessed by calculating the proportion of errors, averaged across the five trials. Error rates for the spatial tapping task were very low, ranging from 0 to 7 percent of total key presses, with a mean (*SD*) of 2.6% (2.0). This translates to approximately 7 errors over the entire duration of the spatial tapping task, or 1.4 errors per 30-second trial.

It is generally accepted in the psychological literature that humans are poor generators of random sequences (Barbasz, Stettner, Wierzchon, Piortrowski, & Barbasz,

2008). Furthermore, while assessing randomness presents significant difficulties as it cannot be directly observed, Towse and Neil (1998) note that departures of randomness can be quantified. Departures from randomness often manifest themselves with uneven distributions of possible options, avoidance of repetitions, and some form of counting (Barbasz et al., 2008). While the ability to generate random sequences was not the priority of the study, data were summarized according to a number of measures reviewed by Towse and Neil (1998) and assessed with the RGCalc software.

Redundancy of responses (*R* score) is a measure used to assess the distribution of responses; how often a participant repeats response choices. An *R* score of ‘0’ indicates no redundancy (perfect equality of response alternatives) while an *R* score of ‘100’ indicates complete redundancy. Redundancy for this sample was low, with a mean *R* score of 1.79 (*SD* = 1.38).

Random number generation (RNG) describes the distribution of response pairs (digrams) as opposed to individual response options. It assesses how often any response alternative follows any other response alternative. Scores can range from ‘0’ to ‘1’, where ‘0’ represents perfect distribution of response pairs and ‘1’ represents complete repetition (predictability) of pair sequences. The mean RNG score for the current sample was .575 (*SD* = .092).

The adjacency score refers to the percentage of paired responses which form adjacent values on the number line. Adjacency scores are presented for both ascending and descending values and can be added to form a combined score. As a percentage score, values can range from ‘0’ to ‘100’ where ‘0’ indicates no neighboring pairs and ‘100’ if the set consists entirely of neighboring pairs. Mean adjacency scores for the

current sample were 25.85 ($SD = 6.46$) for ascending and 25.44 ($SD = 5.61$) for descending adjacency.

As noted above, the rate at which participants counted or key pressed varied with the working memory tasks. Counting and counting/tapping conditions were carried out at a rate of approximately one per second. However, the spatial and random tapping conditions were nearly double that rate. In order to examine whether this increase rate of key tapping was associated with performance on the PDT task, a number of issues were explored. PDT reaction times were first examined to determine if they correlated with generation rate. Participants may have sped up number generation to aid in carrying out this task and inadvertently created a higher cognitive workload, which resulted in the increased PDT reaction time scores. PDT reaction times were not associated with total number of key presses for any of the working memory tasks. Correlations between generation rate and reaction times were lowest for the counting/tapping task ($r = -.009$), followed by random tapping ($r = .137$), spatial tapping, ($r = .143$), and counting only ($r = -.168$). None of the above correlations were significant. Thus, participants who generated the number sequences for the spatial and random tapping tasks at a higher rate were not necessarily those who also had higher reaction times on the PDT task.

To more fully explore whether key tapping rate (response rate) was associated with performance on the number generation tasks, response rate was correlated with the number of errors for the spatial tapping task and scores on the randomization measures reported above. The number of keys pressed during the spatial tapping task was not associated with number of errors committed ($r = .134, p = .474$). However, the total number of key presses on the random tapping trials was associated with two measures of

randomness performance. A significant positive correlation was found between number of key presses and RNG score ($r = .525, p = .002$) and between number of key presses and the ascending adjacency score ($r = .574, p < .001$). Correlations between response rate and the redundancy score ($r = .008$) and descending adjacency scores ($r = .105$) were not significant. Thus, these results show mixed support that participants with higher response rates were also more likely to have less random key presses than those with lower response rates.

Discussion

Experiment 2 assessed the overall difficulty of tasks designed to add workload to each of the three working memory subsystems. The results showed that the counting and key tapping tasks were not equally difficult. Specifically, the phonological counting task was the easiest, followed by the counting and tapping task, and then the spatial tapping task. The random tapping task was found to be the most difficult task, based on the PDT paradigm.

The two most difficult tasks were also associated with an increase rate of key pressing. It is possible that, given the added effort to create specified or random sequences of key presses, participants increased the rate of key pressing as a strategy to perform better on that particular task (e.g., increased the rate of performance so as not to overthink the sequence of key presses). While this strategy may have contributed to a low error rate in the spatial tapping task, it is possible that the increased rate of generation inadvertently created a higher cognitive workload resulting in increased reaction times to the auditory PDT. Regardless, while the rate of key pressing was higher for the spatial

tapping condition, there was no correlation between participants with higher rates of key presses and PDT reaction times.

With regards to the random tapping task, not only was the increased rate associated with poorer performance on the PDT task, it was also associated with impaired ability to create random sequences, as evidenced by higher RNG and adjacency scores. This shows that individuals with quicker number generation rates were also the ones with poorer randomness scores. This result is consistent with research indicating that the randomness of sequences is affected by generation rate (Jahanshahi, Saleem, Aileen, Dirnberger, & Fuller 2006).

Randomness can be difficult to assess. Moreover, it is difficult to compare values of R, RNG, and adjacency values to other studies given the specific parameters set out for this specific experiment. For example, with only a four-key alternative choice option (1, 2, 3, 4), redundancy and adjacency values will be higher than experiments where participants are required to generate random sequences of letters of the alphabet where there are 26 unique alternatives. Even using a set size of 0-9 would produce different values. Unless the parameters in the experimental design are exact, there are no standardized scores for these measures. As such, the use of these measures to assess the randomness of participants' sequences is of limited utility. What it does allow, however, is to be able to say that, in general, participants provided an honest effort to produce random sequences.

With respect to the goals of this thesis, there are three findings to take away that are able to inform further experimentation. First, designing experiments with comparable task difficulty levels is important. As such, Experiment 3 used the counting/tapping task

to more closely approximate the spatial and random tapping tasks without changing the focus of the counting task itself. Second, the increased key-pressing rate found in the spatial and random tapping conditions was unexpected and excessive. Instructions for these tasks need to explicitly specify a rate at which key pressing should take place in order to avoid any confounds of increased generation rate. Finally, the current experiment was important in that it provided a rank-order of difficulty level of the working memory tasks used in Experiment 3, making it possible to statistically control for differences in difficulty (i.e., include working memory task as a control variable) in subsequent analyses.

CHAPTER 4: EXPERIMENT 3

The goal of Experiment 3 was to examine the link between FoV and working memory. As reviewed above, previous research has examined the effects of reduced FoV on performance on a number of basic tasks (e.g., locomotion, object tracking). However, relatively little research (e.g., Gauthier et al., 2008) has considered the possibility that the performance deficits associated with reduced FoV may be due to the increased cognitive demands placed on working memory as a result of storing, maintaining and integrating disparate visual samples when the whole scene cannot be viewed at once. Experiment 3 extended the FoV and working memory literature by assessing the role of working memory's phonological, visuo-spatial, and central executive systems in remembering geons and their locations under restricted FoV conditions.

Experiment 3 used the GMT developed in Experiment 1, along with a dual-task paradigm, to interfere with either the verbal, visuo-spatial, or central executive subsystems. The counting/tapping, spatial tapping, and random tapping tasks examined in Experiment 2 were used as concurrent load tasks on the phonological, visuo-spatial, and central executive subsystems, respectively. As noted in Experiment 2, the counting/tapping task was used in place of counting-only in order to most closely approximate the workload of the other two tasks. The following research questions with their hypotheses were investigated in Experiment 3:

1. Does restricting FoV contribute to poorer performance on the GMT? It was hypothesized that Experiment 3 would replicate the findings of Experiment 1 showing that restricting FoV causes greater geon placement errors, reduces

the proportion of geons replaced correctly, and results in a larger number of attempts required to successfully recreate the geon scene.

2. Does overloading components of the working memory system exacerbate the negative effects of FoV on performance on the geon memory task? Due to the visual and spatial requirements of the GMT, it was expected that stressing the visuo-spatial working memory subsystem would result in poorer performance on the GMT after accounting for the expected negative effect of FoV. It is possible that the phonological working memory system is recruited to aid the visuo-spatial subsystem, particularly with reference to memory for geon identity. As such, it was expected that challenging phonological working memory by restricting FoV and pairing with a concurrent working memory task would result in degraded performance on the GMT. Further, as the mechanism of control over the working memory system, particularly with regards to integration of multidimensional information and integration of repeated sampling expected as the result of restricted FoV, the central executive, too, was expected to be associated with impaired performance on the GMT.

3. Does restricting FoV inhibit the rate of learning one's environment?

Experiment 1 showed that participants required more attempts to successfully recreate the virtual scene under restricted FoV conditions. This suggests a slower rate of learning under restricted FoV. Experiment 3 more explicitly examined the trajectories of the learning curves associated with geon placement errors for wide and narrow FoVs for each of the working memory

groups. It was hypothesized that, given the expected associations between FoV and each component of working memory, learning curves (slopes) over the course of attempts for all three working memory components would be shallower in the narrow FoV condition than in the wide FoV condition.

Methods

Participants

Ninety-two Carleton University undergraduates were recruited. However, three participants were not able to complete the experiment (one due to a power outage and two due to display channel failures). Thus, data are reported for 89 participants (50 females; 39 males). Their ages ranged from 17 to 36 ($M = 19.7$, $SD = 2.97$). Participants were recruited using Carleton University's online sign-up system and were compensated with course credit. Participants had normal or corrected-to normal vision but could not wear glasses that prohibited them from wearing the field-restricting glasses.

Stimuli and Apparatus

The primary task (i.e., GMT) used in Experiment 3 was identical to that of Experiment 1 and was presented on the wide FoV display system. FoV was restricted using modified glasses. Responses to the working memory tasks were recorded using the same response box keypad used in Experiment 2 and connected to the response interface computer.

Design and Procedure

This experiment used a 2 (Load: single vs. dual) x 2 (FoV: (40° vs. 120°) x 3 (WM task: phonological vs. visuo-spatial vs. central executive) mixed-factor design. Load and FoV were within-subjects factors and were blocked and counterbalanced across

participants. Working memory task was a between-subjects factor and was randomly assigned across participants. Participants were first trained on their assigned working memory task to ensure understanding. Participants assigned to the spatial or random tapping conditions completed a one-minute practice trial, which ensured understanding and served as a baseline working memory task performance measure. In order to address concerns of generation rate identified in Experiment 2, an example rate of one number per second was given to participants in the counting/tapping condition and feedback was given as to the rate of key pressing for the spatial and random tapping tasks. Participants then completed a practice trial of the GMT, after which they completed the experimental session.

Participants completed the GMT for two virtual scenes in each FoV condition, for a total of four experimental trials. Within each FoV condition, participants completed one single-task trial (GMT only) and one dual-task trial (GMT + the assigned working memory task). On the single-task trial, the procedure was identical to that of Experiment 1 (30-second environmental learning period followed by the geon replacement recall phase). On the dual-task trial, the secondary working memory task commenced at the beginning of the 30-second learning period. Participants performed the working memory task concurrently with the learning phase of the GMT until the stimuli disappeared. Participants then responded using the same response interface and procedures described in Experiment 1.

Two procedural changes from Experiment 1 should be noted. Whereas in Experiment 1 participants were required to successfully recreate the scene on two *consecutive* trials of the GMT, Experiment 3 required participants to correctly recreate

the scene twice. For example, if a participant successfully completed the task on the third attempt, was incorrect on the fourth attempt, but was again correct on the fifth attempt, the scene was considered complete. Furthermore, participants were restricted to eight attempts to successfully complete a scene on the GMT. These changes were imposed in order to retain as many participants as possible given the high non-completion rate in Experiment 1. Participants took approximately one and a half hours to complete the experiment.

Phonological Working Memory Task. The phonological working memory task was the counting/tapping task tested in Experiment 2. Participants were instructed to count out loud for the duration of the 30-second trial. They were told to count at a rate of approximately one number per second. It was stressed that this was only meant to be a guideline and they should not actively monitor their counting rate such that it distracted them from their other tasks. Each time participants said a number they simultaneously pressed the red button on the response box. It was expected that the counting/tapping task would disrupt the ability to sub-vocally articulate geon identities and their positions within the virtual environment.

Visuo-spatial Working Memory Task. The visuo-spatial task was a spatial tapping task requiring participants to continuously press a series of keys on a response box in a predefined pattern for the duration of the trial. The pattern of button presses was the same as in Experiment 2. The pattern of key presses was limited to four to ensure that central executive resources were not recruited (see Vandierendonck, De Vooght, & Van der Gote, 1998). Participants were specifically instructed to make approximately one key press per second; however, as in the verbal task, participants were instructed to use this as

a guide and not let the key pressing rate distract them from the primary task. Participants were encouraged to not use verbal rehearsal techniques to remember the key press response pattern, but instead to imagine their hands over the keys and use this mental image to successfully remain on track. This was done to ensure that verbal resources would be used for the primary memory task and not for the working memory task.

Central Executive Working Memory Task. Random key tapping was used to tax central executive resources. Instructions for this task were identical to that of Experiment 2. Specifically, participants were instructed to pay special attention not to create patterns in their key presses and were reminded that, if completely random, each key had an equal possibility of being pressed at each key stroke. Participants were instructed to make approximately one key press per second, but to only use this as a guide and not let key pressing rate distract them from the primary task.

Results

Prior to analysis, each dependent variable was screened for outliers, missing data, normality, and homogeneity of variance. Unless otherwise specified, data complied with all assumptions. Dependent measures were considered mutually exclusive in that if a participant was an outlier on one measure, they were not automatically removed from all analysis. As such, the degrees of freedom from the following analyses may vary from one dependent measure to the next.

Each dependent variable was analyzed using a 2 x 2 x 3 mixed-factor ANOVA with Load (single vs. dual) and FoV (120° vs. 40°) as within-subjects factors and WM task (phonological vs. visuo-spatial vs. central executive) as a between-subjects factor. Post-hoc comparisons were made using 95% confidence intervals (Jarmasz & Hollands,

2009). Relational confidence intervals were calculated using the MorePower 6.0 calculator (Campbell & Thompson, 2012). Statistical analyses of these measures are described below. Following the analyses of the dependent measures, a multilevel linear model (MLM) analysis assessing participant learning curves with respect to geon placement errors is reported. Working memory task performance is then assessed.

Number of Attempts to Recreate the Scene

The mixed-factor ANOVA revealed significant main effects for both Load, $F(1,86) = 39.13, p < .001, \eta_p^2 = .313$, and FoV, $F(1,86) = 6.40, p = .013, \eta_p^2 = .069$. There was no effect of WM task, $F(2,86) = .353, p = .704$, suggesting that the three working memory tasks on their own, while of differing difficulty, did not differentially affect performance on the GMT. The ANOVA also revealed a significant three-way Load x FoV x WM interaction, $F(2, 86) = 4.97, p = .009, \eta_p^2 = .104$.

The main effects for Load and FoV revealed that a concurrent working memory task (dual-task condition; $M = 6.56, SD = 1.349$) impaired performance on the GMT relative to that of performing it alone (single-task condition; $M = 5.67, SD = 1.473$) and that a narrow FoV required a greater number of attempts to successfully recreate the virtual scene ($M = 6.28, SD = 1.392$) than a wide FoV ($M = 5.95, SD = 1.310$). A follow up comparison using 95% confidence intervals revealed that the 3-way interaction was driven by a significant Load x FoV interaction occurring in the central executive working memory condition, but not in the verbal or visuo-spatial working memory conditions. As depicted in Figure 12, significantly fewer attempts were required to recreate the scene in the single-task, 120° FoV condition than in the single-task, 40° FoV condition. This difference was not significant in the dual-task condition.

Figure 12. Mean number of attempts required to recreate the scene by working memory task and load conditions. Error bars represent relational 95% CIs (Loftus & Mason, 1994).

Proportion of Geons Replaced Incorrectly

There were significant main effects of Load, $F(1, 81) = 54.623, p < .001, \eta_p^2 = .403$, and FoV, $F(1, 81) = 9.58, p < .001, \eta_p^2 = .106$. The main effect of WM task was not significant, $F(2, 81) = 2.62, p = .079$. The main effects of Load revealed that a greater proportion of geons were replaced incorrectly in the single-task condition ($M = .23, SD = .079$) than in the dual-task conditions ($M = .30, SD = .098$). The main effect of FoV revealed that a greater proportion of geons were replaced incorrectly in the narrow FoV ($M = .28, SD = .098$) condition than in the wide FoV condition ($M = .25, SD = .077$). There was a significant Load x FoV x WM interaction, $F(2, 81) = 4.009, p = .022, \eta_p^2 = .09$.

As depicted in Figure 13, the 95% confidence intervals revealed that the three-way interaction was due to the differential Load by FoV relationships for each WM task group. In the phonological group, a clear Load by FoV interaction existed whereby the proportion of geons replaced incorrectly increased significantly more in the dual-

task/narrow FoV condition than the dual-task/wide FoV condition from both single-task FoV conditions. Conversely, the increase in the proportion of geons replaced incorrectly in the central executive group was not as great in the dual-task narrow condition from the single task/narrow condition as compared to the dual-task/wide FoV condition. There was no evidence of a Load x FoV interaction in the visuo-spatial group. This pattern of results closely mirrored the effects observed in the data for the number of attempts required to complete the scene measure. In sum, the negative effects of a concurrent working memory task on the GMT were exacerbated by narrowing the FoV in the phonological group, mitigated by narrowing the FoV in the central executive condition, and was unaffected by FoV in the visuo-spatial condition.

Figure 13. Proportion of geons replaced incorrectly with 95% CIs (Loftus & Mason, 1994) depicting a significant Load x FoV interaction in the phonological and central executive working memory conditions.

Proportion of Distractor Geons Selected

The mixed-factor ANOVA revealed a significant main effect of Load, $F(1,83) = 18.56, p < .001, \eta_p^2 = .183$. A larger proportion of distractor geons were selected in the

dual-task condition ($M = .046$, $SD = .023$) than in the single-task condition ($M = .035$, $SD = .021$). Neither the main effect of FoV, $F(1,83) = 2.483$, $p = .119$ nor the main effect of working memory, $F(2,83) = 1.306$, $p = .276$, were significant. There was a significant Load x FoV interaction, $F(1,83) = 3.784$, $p = .053$, $\eta_p^2 = .044$. Pairwise comparisons between wide and narrow FoV at each level of Load revealed that participants selected more distractor geons in the narrow FoV condition, but only in the dual task condition. Examination of 95% CIs (see Figure 14) revealed that there was no effect of FoV in the single-task condition but that participants selected significantly more distractor geons in the narrow FoV condition than in the wide FoV condition when carrying out a concurrent working memory task. Thus, these findings suggest that while restricting FoV alone does not impair memory for geon identity, the negative effects of a secondary task are exacerbated by restrictions to the visual field. This effect, however, was not dependent on the nature of the secondary task (i.e., whether phonological, visuo-spatial, or central executive). The three-way interaction was not significant, $F < 1$.

Figure 14. Proportion of distractor geons selected with 95% CIs (Loftus & Mason, 1994) depicting the Load x FoV interaction effect.

Geon Replacement Accuracy

The ANOVA revealed a significant main effect of Load, $F(1,82) = 49.91, p < .001, \eta_p^2 = .378$, indicating that geon replacement accuracy was significantly better in the single-task condition ($M = 18.17, SD = 5.10$) than in the dual-task condition ($M = 23.43, SD = 6.52$). A main effect was also found for FoV, $F(1,82) = 11.789, p = .001, \eta_p^2 = .126$, indicating that replacement accuracy was significantly better in the wide FoV condition ($M = 19.68, SD = 5.20$) than in the narrow FoV condition ($M = 21.92, SD = 5.93$). Additionally, a main effect was also found for working memory group, $F(2,82) = 4.76, p = .011, \eta_p^2 = .104$. Placement errors were smallest in the central executive WM group ($M = 18.91, SD = 3.57$), followed by the phonological group ($M = 22.60, SD = 4.71$) and then the visuo-spatial WM group ($M = 20.95, SD = 5.16$).

A significant three-way Load x FoV x WM group interaction was found, $F(2, 82) = 5.709, p = .005, \eta_p^2 = .122$. As can be seen in Figure 15, the phonological and visuo-spatial WM tasks interfered significantly more with geon placement accuracy in the narrow FoV condition than in the wide FoV condition. In contrast, the effect of restricting FoV appears to be mitigated by the central executive task. That is, there was no increase of placement errors when a central executive WM task was added in the narrow FoV condition.

Figure 15. Geon placement errors with 95% CIs (Loftus & Mason, 1994) depicting the Load x FoV x WM interaction. Phonological and visuo-spatial groups display negative effect of FoV in addition to that of a secondary task.

As in Experiment 1, geon replacement accuracy was also analyzed for only the first three attempts. This was done given the possibility of underestimating the effect of FoV by averaging errors over an entire trial set. There were significant main effects of Load, $F(1,81) = 62.526, p < .001, \eta_p^2 = .436$, FoV, $F(1,81) = 18.397, p < .001, \eta_p^2 = .185$; and working memory task, $F(2,81) = 4.521, p = .014, \eta_p^2 = .10$. Consistent with the previous analysis, geon replacement accuracy was significantly better in the single-task condition ($M = 26.06, SD = 9.92$) than in the dual-load condition ($M = 37.80, SD = 13.07$) and was also significantly better in the wide FoV condition ($M = 29.14, SD = 9.48$) than in the narrow FoV condition ($M = 34.73, SD = 12.57$). Placement errors were smallest in the central executive WM group ($M = 28.12, SD = 7.10$), followed by the phonological group ($M = 32.32, SD = 10.24$) and then the visuo-spatial group ($M = 35.36, SD = 9.47$). The three-way Load x FoV x WM task interaction was significant, $F(2,81) = 7.507, p = .001, \eta_p^2 = .156$. The pattern of this three-way interaction for the first three

attempts was identical to the pattern reported when all trials were analyzed. Specifically, the phonological and visuo-spatial WM tasks interfered with geon replacement accuracy, but only in the narrow FoV condition. In contrast, there was no statistical difference in geon replacement accuracy between the narrow and wide FoV conditions when a central executive WM task was being performed. These data are summarized in Figure 16 below.

Figure 16. Geon placement errors for the first three trials with 95% CIs (Loftus & Mason, 1994) depicting Load x FoV x WM interaction.

In summary, the ANOVAs have shown differing levels of association between FoV, performance, the phonological and visuo-spatial working memory conditions, and the central executive. The expected performance impairments as a result of restricted FoV were found in the phonological working memory group for the proportion of objects replaced incorrectly, geon selection accuracy, and geon replacement accuracy, and for geon selection and geon replacement accuracy in the visuo-spatial working memory group. Findings inconsistent with expectations were found for the central executive group in that restricting FoV did not appear to have the expected negative affect on performance on the GMT for this group.

Multilevel Linear Model

To further explore the relationship between FoV, working memory, and performance on the GMT, the data were analyzed by way of a multilevel linear model (MLM). Although traditionally more prominent a technique for non-experimental research designs, MLM is also appropriate for analyses in repeated measures designs. MLM was designed to address the hierarchical (nested) reality common in many data sets.

One strength of using MLM for repeated measures designs is that it allows researchers to more effectively deal with missing data. MLM is able to effectively deal with missing data and retain the use of an individual participant in the case of attrition, a missed measurement or, as in the design of the current experiment, a particular subject was able to complete the requirements of the experiment in fewer attempts than other participants. This is unlike the repeated measures ANOVA, which uses listwise deletion and eliminates all measurements of the participant if one of measurement is missing.

In the present MLM analysis, data was entered into a 2-level mixed model with attempt number as the time varying covariate. Level 1 consisted of the repeated measures of geon placement errors in each trial attempt. Level 2 represented the nesting of the attempts within each participant. As in the previous analyses, outliers were assessed and considered to be unrepresentative of the sample and removed from the analysis. Thus, 84 participants were included in the analysis. FoV (120° and 40°) and working memory load (no load, phonological, visuo-spatial, central executive) were included in the model as predictors. If a correct geon was not selected, it was not included in the analysis as no error score could be computed for that geon. Thus, the

analysis focused specifically on participants' spatial memory as opposed to a more global measure of performance. Secondary working memory group condition was to be entered into the model to statistically control for differences in secondary task difficulty, as noted in Experiment 2. However, due to a technical problem where working memory task data was not properly recorded, it was not entered into this analysis. Working memory task performance will be discussed further after the MLM analysis.

Prior to conducting the analysis, individual raw scores were examined to observe the overall trend of the data. As can be seen in Figure 17, geon placement errors were high but declined sharply over the first few attempts. After approximately attempt number three, performance leveled off and was relatively stable, with the number of errors decreasing slowly over the next five attempts. Figure 17 shows that placement errors are more accurately described as a curvilinear function of geon placement errors with attempt number. Given that MLM as an analysis falls under the general linear model, the analysis does not function accurately with curvilinear data. As such, to more accurately model the effect of FoV and WM tasks on geon placement errors over the course of a trial set, a piecewise model was employed. A piecewise model allows a single function to be broken up where, in this case, two straight-line slopes were drawn in place of a single slope. Based on observations of the raw data (Figure 17), attempt number three was determined to be a suitable inflection point. Two additional variables based on attempts were defined: 'Early Attempts' included attempts one through three while 'Late Attempts' included attempts four through eight. In this way, the analysis was able to estimate a better fitting model with two slopes rather than a poor fitting model with one unrepresentative slope.

Figure 17. Raw data depicting trajectories of geon placement errors by attempt number for all participants.

To conduct the MLM analysis, a series of models were calculated. First, three unconditional models were computed. A fully unconditional model consisting only of geon placement errors was conducted to present a baseline. Second, two unconditional growth models were calculated, one with the attempt number, which examines how geon placement errors change over the course of a maximum of eight attempts, and the other, a piecewise model, calculated with the imposed restriction of examining how placement errors change within two predefined sets of attempts (Early, Late). The unconditional growth model was included to highlight the importance of conducting the remaining

analyses in a piecewise format and the limitations of the analysis in that it was bound to the general linear model. To allow for the two slopes, two dummy variables were created and each attempt number was recoded to create the two variables described above.

As can be seen from Table 1, in each model, results showed a significant grand-mean geon placement error scores. In the fully unconditional model, a zero slope is assumed. As such, the predicted scores (intercept) estimates the geon placement error scores at 21.18. With no index of time there is limited utility to this model, as it does not account for the ability of participants to accommodate over the course of the trial set. This lack of fit is reflected by the low intra-class correlation (ICC: $\text{intercept}/(\text{intercept} + \text{residual}) = 16.16/(16.16 + 935.04) = 1.7$) indicating that residual variance only accounted for 1.7% of the explained variance in geon placement error scores. With the addition of attempt number (time variant index) in the unconditional growth model (column 2 of Table 1), a slope could be estimated. As such, the new mean at the start of participant's first attempt (intercept) was now much higher at 43.76 and is more representative of the actual data. One way to compare models is by way of a likelihood ratio model test. Using a chi square test of the 2log Likelihood (-2LL) statistic, a likelihood ratio test is used to compare the goodness of fit of two models. Unsurprisingly, comparing the fit statistics indicated that the unconditional growth model provided a statistically better fit to the data than the fully unconditional model, $\chi^2(1, N = 15\,483) = 2\,536, p < .001$.

Table 1.

Model Summaries: Unconditional Models

Parameters	Fully Unconditional	Unconditional Growth	Unconditional Piecewise
<i>Regression coefficient (fixed effects)</i>			
Intercept	21.18 (0.51)**	43.76 (1.16)**	49.83 (1.578)**
Attempt #		-6.08 (0.197)**	
Early			-17.44 (0.702)**
Late			-1.448 (0.166)**
<i>Variance components (random effects)</i>			
Intercept	16.16 (3.301)**	92.37 (17.56)**	187.42 (32.23)**
Residual	935.04 (10.656)**	784.88 (8.98)**	720.35 (8.23)**
<i>Model Summary</i>			
Fit Statistic			
2LL	149,971.043	147,435.099	146,109.550

Note: * $p < .05$, ** $p < .01$.

When compared to the fully unconditional model, the ICC showed that the residual variance of this new model with a single slope was able to account for 10.5% of the explained variance in geon placement scores. However, the model attempted to fit a straight line to the data. Despite providing a statistically better fit to the data than the fully unconditional model, this straight line did not provide a good fit to the data because of the curvilinear trend of the raw data.

As noted previously, the unconditional growth model was included to highlight the importance of the piecewise model. In addition to the intercept (i.e., mean error placement scores at attempt zero), the piecewise model included two additional slope values (Early, Late). As depicted in Table 1, both slope values were significant and negative. Further, the magnitude of slope value for Early Attempts was greater than

Later Attempts. Thus, geon placement error scores declined at a much greater rate during early attempts than during late attempts.

In assessing the overall model, ICCs showed that the residual variance of the unconditional piecewise model was able to account for almost double that of the unconditional growth model. The ICC for the unconditional piecewise model was 0.206. Thus, the residual variance of the piecewise model was able to account for 20.6% of the variance in geon placement errors, leaving 79.4% of the variance to unspecified factors. Moreover, the -2LL test indicated that piecewise model was a better fit than the unconditional growth model, $\chi^2(4, N = 15,483) = 1,325.55, p < .001$.

After assessing the unconditional models, two additional models were constructed in order to include the variables of interest. FoV and WM task were both level 2 predictors and were entered to improve the prediction of geon placement errors. FoV and WM task were entered as categorical variables where FoV consisted of two levels (120°, 40°) and WM task consisted of four levels (no load, phonological, visuo-spatial, central executive). The wide FoV condition was coded '0' while the narrow FoV condition was coded '1'. Given that WM task was a four-level categorical variable, working memory groups were recoded into three dummy variables. In doing so, the 'no load' condition was coded to reflect the reference group. Thus, the WM task variable used in previous analyses was now reflected by 'Dummy1', 'Dummy2', and 'Dummy3' in the statistical software database and corresponded to phonological, visuo-spatial, and central executive working memory groups, respectively.

The first model to be computed was the basic piecewise growth model and included Early Attempts, Late Attempts, FoV, and the WM task variables with geon

placement errors. The second model was built on this basic model and included all interaction terms. Both models are summarized in Table 2.

Table 2.

Model Summaries: Piecewise Models.

Parameters	Main Effects Piecewise		Interactions Piecewise	
	Coefficient	SE	Coefficient	SE
Intercept	44.67**	1.59	39.33**	1.75
Early	-17.45**	0.70	-14.77**	0.89
Late	-1.79**	0.17	-0.51	0.37
FoV	3.13**	0.43	4.68**	1.39
Phonological	7.66**	0.72	14.70	2.18
Visuo-spatial	8.46**	0.72	12.16**	2.20
CE	6.16**	0.70	11.81**	2.13
Early x FoV			-1.24	0.95
Late x FoV			-0.77	0.50
FoV x Phono			7.95*	2.85
FoV x VS			13.79**	2.89
FoV x CE			-4.46	2.79
Early x Phono			-5.57**	1.43
Early x VS			-2.86*	1.43
Early x CE			-2.15	1.38
Late x Phono			-1.05	0.72
Late x VS			-1.15	0.64
Late x CE			-1.50*	0.60
Early x FoV x Phon			-0.89	1.92
Early x FoV x VS			-5.34*	1.93
Early x FoV x CE			0.57	1.87
Late x FoV x Phono			-0.69	0.94
Late x FoV x VS			-0.76	0.86
Late x FoV x CE			1.14	0.87
<i>Variance components (random effects)</i>				
Intercept	183.94**	31.66	175.35**	30.34
Residual	704.28**	8.05	694.52**	7.94
<i>Model Summary</i>				
Fit Statistic				
2LL	145 769.177		145 546.141	

* $p < .05$; ** $p < .01$

Overall, the piecewise model including FoV and WM tasks as main effects (see column 2 of Table 2) was a better fitting model than the piecewise unconditional growth model with two slopes, $\chi^2 (1, N = 15,483) = 340, p < .001$) but did not account for any more residual variance in geon placement errors (ICC = 20.7%). As can be seen in Table 2, there was a main effect of FoV. Given FoV is a dichotomous variable coded '0' for wide FoV and '1' for narrow FoV, the slope parameter for FoV indicated that as FoV 'increased' from wide to narrow, predicted geon placement errors also increased. Significant estimates were also found for each working memory variable. Significant values for a working memory group indicated a statistically significant difference compared to the no-load reference group. As expected, the addition of a working memory task resulted in significantly increased geon placement errors in all three working memory load conditions.

The full piecewise model including all main effects and interactions (column 4 of Table 2) provided a significantly better fit than the piecewise model including only main effects, $\chi^2 (28, N = 15,483) = 223.036, p < .001$). The piecewise model revealed a significant effect for Early Attempts, $t (286.5) = -16.502, p < .001$, but no significant effect for Late Attempts, $t (14\ 682.82) = -1.373, p = .170$). Thus, collapsed across all FoV and WM conditions, a large decrease in errors occurred in the first three attempts, after which no further decreases of placement errors were of significance.

Because of the way dummy variables were coded for working memory task conditions, the no-load, wide FoV ('0, 0') condition represented the baseline measurement. As mentioned above, all working memory conditions were compared to the no-load baseline condition. As in the simplified main effects model above, a

significant main effect was found for FoV, indicating that geon placement errors in the narrow FoV condition were significantly greater than the wide FoV condition. Additionally, geon placement errors in all three working memory groups were significantly greater than that of the baseline no-load condition. While Table 2 provides a summary of the model and significant interactions, unlike ANOVA and regression, the interpretations of these interactions are not straightforward. As such, using the model equation and substituting the coded values to calculate predicted values is recommended for interpretation of the full MLM model. Figure 18 presents the calculated predicted values of each working memory group for each attempt number separately for wide and narrow FoV conditions to illustrate the predicted trajectories or ‘learning curves’ of geon placement errors.

As depicted in Figure 18, in both wide and narrow FoV conditions, the no-load condition represented the baseline measurement and clearly represents the lowest magnitude of predicted geon placement errors. In the wide FoV condition, all three working memory groups had similar geon placement error magnitudes for Early Attempts and the magnitude of those placement errors declined at virtually the same rate. Over the last number of attempts (i.e., Late Attempts), placement errors converged so that errors made by participants completing any working memory task were indistinguishable from the no-load condition. Thus, there was no significant difference in predicted geon placement errors between working memory conditions in the wide FoV condition on Late Attempts. Moreover, the slope for Late Attempts was not statistically significant, indicating that it did not differ significantly from zero. This lack of slope reflects the fact that participants were required to place the geon within a certain distance of the exact

Figure 18. Predicted trajectories of geon placement errors for wide (top) and narrow (bottom) FoV conditions.

location to be considered correct and likely reflects a floor effect. In any case, the model as it is defined here does not predict a significant reduction of geon placement errors after the third attempt.

In the narrow FoV condition, predicted geon placement errors for the phonological and visuo-spatial groups were higher at attempt one than those of the no-load condition and central executive. However, by the third attempt, geon placement errors for the phonological and visuo-spatial groups were predicted to be relatively close to what they were in the wide FoV condition. As depicted in Figure 18, geon placement errors in the phonological and visuo-spatial working memory conditions were predicted to be just less than 20 feet in the wide FoV condition but just over 20 feet in the narrow FoV condition. However, with a somewhat steeper slope for Late Attempts, the magnitude of errors in these groups declined to equal that of all other groups by the end of the eighth trial.

Finally, the piecewise interaction model produced a significant Early Attempt x FoV x Visuo-spatial interaction. In order to more clearly understand this interaction, predicted geon placement errors for this group were calculated. As depicted in Figure 19, predicted geon placement errors converged between wide and narrow FoV conditions as the attempt number increased. This interaction indicated a significant difference in predicted geon placement errors between wide and narrow FoV at the first attempt, but this difference disappears by the third attempt. This interaction was unique to the visuo-spatial working memory group.

Figure 19. Predicted geon placement errors as a function of attempt number and FoV condition for the visuo-spatial working memory group. Magnitudes of placement errors in narrow FoV condition were initially greater, but decreased quicker than those in the wide FoV condition over the first three attempts.

In summary, the current MLM analysis was conducted to examine the trajectories of the learning curves associated with the various FoV/WM conditions. Examining the predicted values calculated from the full piecewise model offers unique insight into this relationship. As mentioned previously, intercepts and slopes of the three working memory conditions were nearly identical. However, in the narrow FoV condition, the intercepts of the phonological and visuo-spatial conditions were significantly greater and the trajectories of their slopes steeper than those of the wide FoV condition and the central executive and no-load conditions under restricted FoV. Interestingly, by the end of the third attempt, geon placement errors in these two working memory groups approximated those predicted in the wide FoV condition. The implications of this differential trajectory will be discussed below.

Working Memory Task Performance

Due to an unknown technical problem during data collection where task data was not properly recorded, only a fraction of the secondary task data was available for analyses. Voice recordings and key presses were not available for any participants in the phonological counting/tapping task. Key presses for the spatial and random tapping tasks were recorded successfully for a one-minute baseline trial for each participant. However, in-trial key presses were only recorded for approximately half of the participants. Further, of that data, only a small percentage (approx. 30%) of trials were successfully recorded within each successfully recorded participant. Fortunately, however, if a trial was recorded, data was recorded for the full trial. Therefore, error and randomness scores could be calculated for those trials.

Given the data was missing due to a technical complication and was not specific to the participants themselves, the missing data was considered random and was assessed for the potential of using it to inform performance on the working memory tasks. Given that performance (e.g., randomness scores) in Experiment 2 was calculated for each trial and then averaged over the total number of trials completed, it was possible to calculate performance scores in the same manner for Experiment 3 and retain the ability to explore performance on the spatial and random tapping tasks, albeit with limited utility.

As noted, assessment of the phonological counting/tapping task was not possible as voice and key presses were lost. However, as counting was done aloud and in the presence of the experimenter, it could be confirmed that participants did, in fact, carry out this task. Unfortunately, as data was not available, comparisons could not be made regarding the rate of number generation. Performance on the spatial tapping task was

assessed in the same manner as in Experiment 2. The proportion of sequence errors was calculated by dividing the number of errors made by the total number of key presses made by that participant. In this way, error rate was calculated without reference to trial, *per se*, but rather overall performance. Examination of overall errors instead of a trial by trial basis allowed for a meaningful examination of spatial tapping performance despite the error in data collection. The proportion of errors in the baseline measure in Experiment 3 was very low ($M = .029$, $SD = .024$) and was comparable to the proportion of errors made in Experiment 2 ($M = .026$, $SD = .02$). An independent samples *t*-test revealed no statistically significant difference between these two means, $t(58) = -.438$, $p = .663$.

A paired-samples *t*-test was conducted to assess whether error rates differed between pre-trial baseline performance and in-trial (i.e., dual task) performance for participants whose data was successfully collected for both the baseline and in-trial tests of Experiment 3 ($n = 18$). The *t*-test revealed that the proportion of in-trial errors ($M = 0.059$, $SD = .044$) was significantly greater than the proportion of baseline trial errors, ($M = .029$, $SD = .028$), $t(17) = -4.450$, $p < .001$, $d = -1.05$. Thus, performance on the spatial tapping task was significantly impaired when completed concurrently with the GMT.

Consistent throughout the analyses reported above was that performance on the GMT appeared to suffer no additional negative effects when a concurrent central executive (e.g., random tapping) task was paired with the narrow FoV condition. According to the results of Experiment 2, the random tapping task used to tax the central executive subsystem was the most difficult and resulted in greatest cognitive interference. As such, it was thought possible that participants dropped this task to preserve their

performance on the GMT. In order to explore this possibility, random tapping task performance was examined. Means and standard deviations of randomness measures are provided in Table 3.

Table 3.

Mean Scores (*SD*) of Randomness Measures for Experiments 2 and 3.

	<i>n</i>	<i>R</i>	RNG	Adjacency Ascending	Adjacency Descending
E2	58	1.79 (1.38)	.575 (.092)	25.85 (6.46)	25.44 (5.61)
E3 Baseline	54	1.47 (1.31)	.639 (.037)	27.31 (6.88)	27.58 (6.38)
E3 Baseline (subset)	51	1.05 (.082)	.628 (.037)	25.79 (6.87)	25.48 (5.04)
E3 Trials	50	3.00 (1.94)	.581 (.065)	30.87 (9.91)	26.73 (8.77)

Given that working memory task data from the actual experimental trials were sparse, secondary task performance was first assessed by comparing performance of participants during the baseline testing in the current experiment to those of Experiment 2. As the scores on the measures for assessing randomness are influenced largely by the specific parameters of the experiment thereby limiting the utility of comparisons of other studies (e.g., alternative set size, number of responses possible, etc.), this comparison served as loose standardization of scores. Independent-samples *t*-tests were conducted on each randomness measure reported in Experiment 2 between Experiment 2 data and baseline data from all participants in Experiment 3. A Levene's test indicated that RNG

scores violated the assumption of homogeneity of variance. As such statistics where equal variance was not assumed are reported for this variable.

Of the four measures, only RNG scores differed significantly between Experiment 2 and the baseline measure of Experiment 3, $t(43.476) = -3.628, p = .001, d = .88$. Specifically, mean RNG scores were significantly greater in the Experiment 3 baseline group ($M = 0.639, SD = 0.037$) than in Experiment 2 ($M = 0.575, SD = 0.092$). Means of R -score, $t(59) = .897, p = .413$, ascending adjacency scores, $t(59) = -.854, p = .397$, and descending adjacency scores, $t(59) = -1.394, p = .169$, were not significantly different between Experiment 2 and Experiment 3 baseline scores. Thus, RNG scores indicate that baseline scores in Experiment 3 were less random than Experiment 2 but the other three measures indicate they were of comparable randomness.

To explore the possibility that participants neglected the secondary random key tapping task in the experimental trials of Experiment 3, scores on the four measures of randomness from the experimental (in-trial) trials were compared to the baseline (pretrial) data collected in the introduction of the experiment. Of the 30 participants randomly assigned to the central executive working memory condition, partial data was only successfully collected for 15 participants. After screening the data, one further participant was removed because of an extreme z -score on one of the measures of randomness of over six standard deviations away from the mean. Thus, the current analysis was conducted on a sample size of 14. This sample, however, was considered a random sample of the central executive working memory group.

A series of repeated measures t -tests revealed significant differences between pre-trial and in-trial scores for two of the four measures of randomness. Differences in means

were significant for *R*-score values and RNG scores. In-trial scores were significantly higher than pre-trial scores for *R*-scores, $t(13) = -4.618, p < .001, d = 1.233$, indicating that the in-trial response sequences were more repetitive than the pre-trial sequences. Alternatively, in-trial RNG scores were significantly lower than baseline RNG scores, $t(13) = 3.534, p = .004, d = .944$, indicating the sequence of trial score button pressing consisted of less predictable and repetitive pairs of numbers. There were no significant differences between baseline and trial scores for either ascending, $t(13) = -1.567, p = .141$, or descending, $t(13) = -0.624, p = .543$, adjacency scores. Thus, these analyses indicated that participant response sequences were *less* random (i.e., more repetitive) during the experimental trials only for the *R*-score, but *more* random than the pre-trial for the RNG scores. Adjacency scores did not show any difference between pre-trial and in-trial scores.

Discussion

Experiment 3 examined the relationship between FoV restrictions and working memory. Participants performed either a phonological, visuo-spatial, or central executive WM task concurrently with a GMT. The results replicated those of Experiment 1 in showing that restricting an observer's FoV impaired performance on the GMT. Consistent with Experiment 1, the only measure to not show an effect of FoV was that of geon selection accuracy, albeit only in the single-task condition. This measure did reveal a performance decrement associated with reduced FoV in the dual-task conditions.

The results of Experiment 3 indicated that FoV affected working memory. According to the original hypothesis, FoV was expected to negatively affect all three components of working memory. This hypothesis was not fully supported. While

evidence was provided supporting the effect of FoV on visuo-spatial and phonological working memory, the data did not support this hypothesis for the central executive.

The concurrent visuo-spatial working memory task was originally hypothesized to have a larger negative impact on performance on the GMT than both the concurrent phonological and central executive tasks. Further, interactions between FoV and working memory groups were predicted such that the negative impact of the working memory tasks on GMT performance would be greater when FoV was reduced. The results from the current experiment indicated that FoV interacted with both the visuo-spatial and phonological tasks, though inconsistently with regard to which interaction effect was stronger. Specifically, while no Load x FoV interaction effect was found for either phonological or visuo-spatial WM tasks in terms of the number of attempts required to recreate the scene, the hypothesized Load x FoV interaction was observed in the *phonological* WM condition with respect to the proportion of geons replaced incorrectly. With regard to the measure of total placement errors, Load x FoV interactions were found in both the phonological and visuo-spatial conditions and were of comparable magnitudes. Finally, both the visuo-spatial and phonological working memory groups produced the hypothesized Load x FoV interaction effects for the measures examining the geon selection and geon placement errors.

One possible reason that interactions between FoV and working memory load task were not found in on all measures for the visuo-spatial working memory group may be due to the task chosen to tax the visuo-spatial system. The visuo-spatial working memory task (spatial tapping) used in this thesis was arguably more spatial-oriented than visual. According to Logie (1995), visual and spatial information are stored in separate

buffers. As such, performance on the more visual components of the GMT may have been preserved, in part because only the spatial component of the visuo-spatial subsystem was being taxed, leaving visual resources available to carry out aspects of the memory task.

One unexpected result was that, on multiple measures, the impairment caused by restricting the participant's FoV was buffered by the central executive WM task. That is, the effect of restricting FoV observed in the single-task condition on both measures of general performance (number of attempts to recreate the scene and proportion of geons replaced incorrectly) was statistically eliminated in the central executive WM (dual-task) condition. In fact, in terms of the number of attempts required to successfully re-create the scene for the central executive group, there was no difference between the single and dual-task conditions in the narrow FoV condition. Moreover, while FoV and Load had additive effects on placement errors in both the phonological and visuo-spatial working memory groups, the central executive group displayed the opposite. While placement errors were significantly greater in the dual-task condition than in the single-task condition under wide FoV, there was no statistical difference when under narrow FoV. Interestingly, the pattern of results observed in the central executive condition is opposite to what was expected. That is, in three out of the five measures, performance equaled that of the narrow FoV condition and on one measure (number of attempts), even appeared to have *benefitted* participants when completing a concurrent central executive task.

Given the random tapping task used to tax the central executive was found to be more difficult than all other working memory tasks, it was thought that participants may

have neglected or dropped the random tapping task in order to preserve performance on the GMT. However, according to performance measures (e.g., randomness) of the random tapping task, this was not likely. While significant differences of randomness were found for *R*-score and RNG, the former indicated that in-trial sequences were less random than baseline scores while RNG scores indicated that in-trial sequences were more random than baseline score. The adjacency measures did not indicate a difference between baseline and in-trial randomness quality. As each measure assessed a different aspect of randomness, it is possible that these aspects were, in fact, differentially affected. However, for the purposes of the current experiment, it was evident that participants did not neglect this task. Even taking into account the limitations of this analysis given the lost data, it is evident that participants continued to carry out the random tapping task to the best of their abilities given the difficult nature of this task. In comparison, in-trial performance on the spatial tapping task was significantly degraded when completing it concurrently with the GMT when compared to the pre-trial baseline tasks. As such, that participants neglected the random tapping task is not a viable explanation for the current results. The impact of FoV on the central executive will be discussed further in the general discussion.

The third goal of Experiment 3 was to examine the learning curves associated with the magnitude of geon placement errors and FoV. According to the multi-level model, predicted values based on FoV and working memory tasks indicated that under restricted FoV conditions, taxing the phonological and visuo-spatial working memory tasks predicted greater errors to start, but with help from a steep learning curve, participants were able to adapt to the restricted FoV environment and, by approximately

the third attempt, displayed no negative effects of FoV. The implication of this finding with regards to the flight environment will also be discussed in further detail in the general discussion.

CHAPTER 5: GENERAL DISCUSSION

Field of view restrictions are known to negatively affect locomotion (Toet et al., 2007; 2008), depth perception (Fortenbaugh et al., 2007), visual search (Wells et al., 1988), target tracking (Wells & Venturino, 1990), and the ability to form spatial representations of the environment (Gauthier et al., 2008). In the flight environment, FoV restrictions have been shown to contribute to decrements in flight performance (Jennings & Craig, 2000), modified visual scan patterns (Estock et al., 2007) and increased pilot workload (Gallimore et al., 1998). Most explanations of these performance impairments have focused on the physical constraints caused by FoV restrictions including the lack of peripheral visual cues. The goal of this thesis was to examine whether performance impairments caused by FoV restrictions could also be attributed to the cognitive load placed on working memory. Three experiments were conducted to examine the effect of FoV restrictions on working memory.

Experiment 1 examined the impact of FoV on GMT performance. Restricting participants' FoV resulted in decreased performance on the GMT. Specifically, participants required a greater number of attempts to complete the task, replaced a greater number of geons incorrectly, and made greater errors when replacing the geons back to their original locations in narrow FoV conditions than in wide FoV conditions. Restricting FoV, however, did not affect the ability to remember the *identity* of geons in the visual array. This suggests that FoV restrictions interfered with spatial working memory, which is responsible for the ability to learn and/or remember the placement of objects in a visual environment.

Working memory research has relied heavily on a dual-task paradigm in which secondary tasks that selectively interfere with one working memory subcomponent (e.g., the phonological loop) are used to examine the working memory demands of a concurrent primary task. Experiment 2 identified the relative difficulties of the secondary working memory tasks that were to be used in Experiment 3: it was important to understand the differential workload levels that would be levied against participants in subsequent testing when they would be asked to carry out these working memory tasks simultaneously with the primary GMT. Experiment 2 showed that the counting task was least difficult, followed by the counting/tapping, spatial tapping, and random tapping tasks, respectively. In order to approximately match the working memory tasks in terms of difficulty, the results from Experiment 2 informed the decision to utilize a counting/tapping task instead of a simple counting task as the task for taxing phonological working memory in Experiment 3.

Experiment 3 further examined the relationship between FoV restrictions and working memory by having participants perform the GMT concurrently with either a phonological, visuo-spatial or a central executive working memory task. Experiment 3 replicated findings from Experiment 1 showing that restricting FoV impaired performance on the GMT. More importantly, Experiment 3 also supported the notion that restricting FoV increases the cognitive demands placed on working memory. Specifically, the phonological and visuo-spatial working memory subsystems were identified as being sensitive to FoV restrictions. Contrary to expectations, however, the central executive was not negatively affected by reductions to the visual FoV. Experiment 3 also provided evidence for adaptation to the restricted FoV environment.

While FoV restrictions had a large negative impact on initial performance, this impairment was short-lived as evidenced by the rapid reduction in geon placement errors. By the third attempt, geon placement errors under restricted FoV conditions were similar to those under normal viewing conditions.

Theoretical Account

FoV and Phonological and Visuo-spatial Working Memory

The pattern of results observed in the present research suggests that both visuo-spatial and phonological working memory subsystems are used to perform the GMT. This finding supports the view that visual information can be coded both phonologically and visuo-spatially (e.g., Baddeley, 2012; Johansdottir & Herdman, 2010; Logie et al., 2000). The counterintuitive finding that phonological resources are used in a visual task can be explained if one assumes that secondary memory systems (e.g., the phonological system on a visual task) are recruited when the primary working memory system (e.g., the visual-spatial system on a visual task) is overwhelmed. Further, it is not unreasonable to assume that the phonological and visual-spatial subsystems are continuously active on complex tasks (e.g., the GMT) as a form of complementary processing to maximize efficiency and performance. On the GMT, for example, phonological working memory may have been used to support the visual-spatial memory subsystem by providing verbal codes to identify prototypical geon features (e.g., “green cube”, “purple rectangle”). In doing so, the sub-vocal articulation of geon feature names engaged the phonological working memory subsystem on what is, at face value, a visual-spatial task.

The present results are consistent with the hypothesis that FoV restrictions increased the demands the visuo-spatial subsystem, as indexed by decreased performance

on the GMT. Given the visual and spatial nature of the GMT, it was not surprising that reducing the visual field would increase the difficulty of processing an already complex visual scene. The impairments in performance (e.g., greater number of attempts required to recreate the scene, greater proportion of geons replaced incorrectly, and poorer geon replacement accuracy) support the hypothesis that reducing FoV negatively impacts visuo-spatial working memory; however, that participants retained the ability to remember object identities suggest that this effect may have been due to strain on the spatial component of visuo-spatial working memory as opposed to the visual component. The inclusion of both a specific spatial and visual secondary task may have helped identify differential effects of FoV on visual and spatial working memory.

The data from this thesis also support the hypothesis that FoV restrictions increased the demands on the phonological subsystem. Specifically, performance on the GMT was impaired when FoV restrictions were paired with a secondary phonological working memory task. One of the goals of this thesis was to explore the possibility that phonological working memory can be recruited to help store and maintain visual information that may not be within immediate view. As suggested by Johansdottir and Herdman (2010) (see also Baddeley et al., 2001), phonological resources can be directed to hold (e.g., rehearse) information for objects that are out of immediate sight. With a wide FoV, more objects are in sight at one time and, thus, this assistance, while still beneficial, may be minimal. However, under restricted FoV conditions, this assistance from phonological working memory may become critical as the demands on visuo-spatial working memory become overwhelming. Under restricted FoV conditions where more aspects of the environment are out of view, the phonological system too may not be able to

meet the demands of the task given the limited capacity of working memory, resulting in decreased performance. Though not direct, that the phonological system was more strained under restricted FoV provides circumstantial support for this claim.

The results reported here indicated that with no secondary working memory task, FoV restrictions did not impair memory for geon identities (e.g., geon selection accuracy). It is possible that, under low workload conditions, FoV restrictions served to direct attention almost exclusively towards the geons, enabling better recall for geon identity, but limiting the amount of information encoded about the spatial relationships between the geons. Consider Figure 20a, where a substantial section of the visual environment is shown. When viewing this scene under normal viewing conditions, an observer may first quickly scan the environment and then direct their attention toward the geon(s) of interest. While this initial scan may be very quick, thereby limiting the amount of information of which the viewer is consciously aware, information regarding geons and their spatial relationships may be collected (Oliva, 2005; Potter, 1976). With a restricted FoV, on the other hand, the *gist* of a scene may not be obtained (i.e., objects may be identified, but their spatial relationships are not attended to). Moreover, on successive viewings, the observer may intentionally direct their attention to these key locations, further limiting the accrual of knowledge about the spatial relationships between these geon locations (see Figure 20b). Research on visual perception indicates that when viewing complex environments, an observer's gaze does not wander aimlessly throughout a scene. Instead, attention is endogenously and/or exogenously guided such that an observer is selective and accurate in their visual samplings (Chun & Nakayana, 2000). Chun and Nakayan suggest that observers focus on the important details within a

scene in order to preserve resources and not overload the visual memory system. Under normal viewing conditions, the process of identifying important details allows the observer to obtain spatial information about the environment. With FoV restrictions, however, even in first scanning the scene for the important components, the observer may be unable to obtain the necessary spatial information to formulate a mental representation of the layout of the environment – much less be able to recreate a scene, as was required in the GMT. Moreover, if, upon subsequent viewings of the same environment, attention is immediately focused on objects within that environment, it is possible that information regarding the spatial relationships between objects is not prioritized. Thus, while restricted FoV may allow for more focused attention on specific features of an environment, resulting in better memory for those features, this focus may take away from identifying spatial relationships between these features.

a)

b)

Figure 20. Example view of visual scene with no FoV restriction (a) and simulated FoV restrictions (b). Under normal viewing conditions, the viewer may scan globally obtaining geon and spatial information on initial glances. Under restricted FoV conditions, attention may be focused quickly on geons of importance, neglecting the spatial relations between them.

FoV and the Episodic Buffer

While not explicitly explored in this thesis, the evidence for the activation of both phonological and visuo-spatial working memory subsystems on the geon memory task suggests the involvement of the episodic buffer. The episodic buffer is a multidimensional storage system used to integrate and store verbal and visuo-spatial information, along with information from long-term memory. Baddeley initially conceived the episodic buffer as an active system responsible for integrating information from various locations (Baddeley, 2000), but amended his hypothesis, describing the episodic buffer as only a passive store (Baddeley, 2012). Regardless of whether phonological and visuo-spatial information is integrated *within* the episodic buffer or in an undefined working memory subsystem, when both phonological and visuo-spatial components are used to process visual information, the buffer must, by definition, be used to store this integrated multidimensional (or more appropriately, multi-code) information.

The GMT used in the current thesis required participants to accumulate visual information from a static scene with each successive viewing. Evidence from the current research indicates that with FoV restrictions, the accumulation of visual details (e.g., geon features) was more difficult than in wide FoV conditions. This was likely due to the increased number of samples required to create an accurate mental representation of the scene when compared to normal viewing conditions. Given the limited capacity of working memory, participants may have relied on the transfer of information from working memory to LTM with every viewing to maintain a stable representation of the scene and the geons therein. Because of the additional demands placed on working

memory under restricted FoV conditions, the transfer of information from working memory to LTM would become increasingly important to ensure the successful completion of the GMT.

The static nature of the GMT allowed for multiple samplings of the identical environment. Field restricting devices such as HMDs are used for training and NVGs are used in various environments, including the cockpit environment. These applications are dynamic and users do not have the opportunity to review the exact same scene multiple times. Thus, the opportunity to utilize LTM to assist in accommodation to the FoV restrictions may be dramatically reduced. It is possible that this transfer of information to LTM would be less important in dynamic environments given that a previously stored version of the environment in LTM would have to be continually updated to match the current environment. At that point, it would seem more feasible to simply maintain a current representation of the dynamic environment in working memory. Maintaining the representation of a dynamic environment in working memory would therefore be more taxing than maintaining a static one. Future research should explore accommodation to FoV restrictions in real-life, dynamic settings.

If it can be assumed that multidimensional information (e.g., phonological and visual-spatial codes) is stored in the episodic buffer and that the episodic buffer is responsible for linking working memory with LTM, then it stands to reason that the episodic buffer played a crucial role in the GMT. As discussed above, both phonological and visuo-spatial working memory systems were activated when FoV was reduced. Further, it was suggested that the transfer of information from working memory to LTM became increasingly important when FoV was restricted. Thus, not only is the episodic

buffer activated when performing the GMT, it is increasingly relied upon under restricted FoV conditions.

FoV and the Central Executive

On complex tasks such as the GMT, both visuo-spatial and phonological working memory subsystems are used. According to Baddeley (2000; 2012), the central executive is essential for integrating information from these two subsystems. Logically then, it follows that the central executive should be involved in the GMT. However, Experiment 3 showed that taxing the central executive using a random tapping task did not impair performance on the GMT. While it is possible that the random tapping task did not adequately strain the central executive, the results from Experiment 2 indicated that the random tapping task was the most difficult secondary task. As such, it would be expected that the level of strain on the central executive should have been sufficient. The data also showed that participants were performing the random tapping task while encoding information on the GMT. Given that there is every reason to believe that the central executive was involved in performing the GMT and given that random pattern generation is the most commonly used approach of taxing the central executive, it is surprising that the GMT was not affected by the secondary random tapping task.

While FoV restrictions strained the phonological and visuo-spatial systems, performance on the GMT suggests that reducing FoV may have eased the workload on the central executive relative to the expected increase seen in the phonological and visuo-spatial subsystems. Specifically, the expected performance impairments were not found in the narrow FoV, dual-load central executive condition. Under normal viewing conditions, countless information and detail is available to be processed. The central

executive must ensure that resources are allocated appropriately. A narrow FoV may effectively play the same role as the central executive by limiting the amount of information available for processing at any given moment. Restricting FoV could therefore be thought of as a physical focuser of attention, a task that is typically performed cognitively by the central executive. For example, instead of attempting to process geon features and the spatial relationships between geons in parallel, only one of these scene elements may be processed at a time through the systematic accumulation of information afforded by FoV restrictions. Or, instead of a parallel versus serial processing distinction, FoV restrictions may force working memory to more fully process smaller samples of the visual scene before the intake of additional information from other portions of the visual scene, which could overwhelm the system. In both cases, smaller amounts of information are held in working memory before being transferred to LTM. However, with FoV restrictions requiring the system to take more visual samplings, this information transfer to LTM is done more often. In this way, FoV restrictions may serve to physically segment the scene into smaller chunks or episodes, which may make perceiving more manageable, at least in the context of the task demands associated with the GMT. While this physical segmentation of the scene may place additional strain on the phonological and visuo-spatial subsystems, along with the episodic buffer, the central executive, in terms of its attentional control responsibilities, may be less taxed.

Learning

Research examining the effects of restricted FoV indicated that while restricting FoV negatively impacts flight performance in a number of ways, pilots were able to adapt to these restrictions and overcome these impairments to a point where they could still

successfully carry out their mission (e.g., Covelli et al., 2010). These findings are consistent with first hand reports from military transport pilots who noted that while NVGs require time, experience, and training to be able to become proficient, once proficient, accommodation to the restricted FoV environment is relatively rapid and dramatic. The accommodation to restricted FoV conditions was assessed and confirmed here via the MLM analysis. While the effects of taxing working memory on the GMT were evident when FoV was restricted, these impairments were negligible past the third viewing attempt. This suggests that the cognitive system is able to adjust to the challenges associated with restricting FoV. As discussed above, it is likely that the transfer of information from working memory to LTM played a crucial role when performing the GMT. It is possible that the participants who quickly transferred specific (e.g., geon identity and location) information to LTM were able to accommodate to FoV restrictions more quickly than those who attempted to maintain too much information in working memory. Once the environment was learned, working memory resources may have only been required to update and maintain the scene-specific information held in LTM, possibly via the episodic buffer.

Conclusions

The results of the present thesis highlight the importance of cognitive functioning when faced with visual FoV restrictions. Not only do FoV restrictions affect the physical/anatomical activation of the peripheral pathways, as shown in previous research; the results of this thesis provide support for the notion that FoV restrictions also affect the cognitive structures that process and temporarily maintain visual information, specifically, working memory. Thus, a major contribution of this thesis is that it has

provided a more complete account of the affect of FoV restrictions than the physical explanations alone.

The findings of this thesis offer important contributions to the working memory literature. First, while both working memory and FoV have been extensively researched, this thesis was the first to link FoV restrictions to working memory. The present research suggests that this pairing was overdue and that future research should continue to explore how FoV restrictions affect cognition in various other domains and tasks. Second, this thesis adds depth to existing working memory and FoV literatures. For example, the current thesis provided additional support to the notion that phonological working memory is able to assist other components of the working memory system, ensuring efficient functioning. It also highlights the need for the episodic buffer, which is important for ensuring that both phonological and visuo-spatial information is integrated and accessible. The results presented here also highlight the need to continue investigating the lesser-known components of working memory, such as the central executive and episodic buffer. Taken together, the findings showcase the flexibility of the working memory system.

A third contribution of note is that this thesis exemplified the utility of the MLM analysis, a technique not common in experimental research. Although MLM has been used for a number of decades, the analysis has yet to be established as a viable and common means of analyzing experimental data. The MLM analyses used in this thesis complemented the traditional ANOVA analyses and provided a more complete picture of the relationship between FOV and working memory under the specific parameters of this research.

In conclusion, the current thesis represents a step toward understanding visual field-restrictions and their physical and psychological implications. This thesis emphasized the importance of FoV in the context of the NVGs in the flight environment; however, this is only one application where FoV is important. Indeed, people are surrounded by visual FoV restrictions in their every day lives, whether it be driving a car, wearing a motorcycle helmet, wearing sunglasses, or impairments causes by eye disease or injury. While technologies afford incredible benefits, they also come with important limitations. Understanding the human factors associated with visual field-restricting technologies will allow for appropriate and responsible applications of these technologies and ensure that users are properly trained.

References

- Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: Gen*, 135, 298-313.
- Arthur, K. W. (2000). Effects of field of view on performance with head mounted displays. *Unpublished Doctoral Dissertation, Department of Computer Science, Chapel Hill, University of North Carolina.*
- Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.
- Baddeley, A. D. (1990). *Human memory: Theory and practice*. Hove: Lawrence Erlbaum Associates.
- Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology*, 49, 5-28.
- Baddeley, A. D. (1998). Recent developments in working memory. *Current Opinions in Neurobiology*, 8, 234-238.
- Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, 4, 417-423.
- Baddeley, A. D. (2007). *Working memory, thought and action*. Oxford: Oxford University Press.
- Baddeley, A. D. (2012). Working memory: Theories, models, and controversies. *The Annual Review of Psychology*, 63, 1-29.
- Baddeley, A. D., Allen, R. J., & Hitch, G. J. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia*, 49, 1393- 1400.
- Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. Bower (Ed.), *The*

- psychology of learning and motivation* (pp.47-90). New York: Academic Press.
- Baddeley, A. D., Chincotta, D. M. & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General*, 130, 641-657.
- Baddeley, A. D., Gathercole, S. E., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, 105, 158-173.
- Baddeley, A. D., Logie, R., Bressi, S., Della Sala, S., & Spinnler, H. (1986). Dementia and working memory. *Quarterly Journal of Experimental Psychology*, 38A, 603-618.
- Baddeley, A. D., Thompson, N., & Buchanan, M. (1975). Word length and the structure of memory. *Journal of Verbal Learning and Verbal Behaviour*, 1, 575-589.
- Baddeley, A. D., & Wilson, B. (2002). Prose recall and amnesia: Implications for the structure of working memory. *Neuropsychologia*, 40, 1737-1743.
- Barbasz, J., Stettner, Z., Wierzhon, M., Piotrowski, K., & Barbasz, A. (2008). How to estimate randomness in random sequence generation tasks? *Polish Psychological Bulletin*, 39, 42-46.
- Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, 94, 115-147.
- Brugger, P., Monsch, A. U., Salmon, D. P. & Butters, N. (1996). Random number generation in dementia of the Alzheimer type: A test of frontal executive functions. *Neuropsychologia*, 34, 97-103.
- Campbell, J. I., & Thompson, V. A. (2012). MorePower 6.0 for ANOVA with relational

- confidence intervals and Bayesian analysis. *Behavior research methods*, 44, 1255-1265.
- Chong I., Mirchi T., Silva H.I., & Strybel T. Z. (2014). Auditory and visual peripheral detection tasks and the lane change test with high and low cognitive load. *Proceedings of the Human Factors and Ergonomics Society*. 2180-2184.
- Chun, M. M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition*, 7, 65-81.
- Conrad, R. & Hull, A. J. (1964). Information, acoustic confusion, and memory span. *British Journal of Psychology*, 55, 429-432.
- Covelli, J. M., Rolland, J. P., Proctor, M., Kincaid, J. P., & Hancock, P. A. (2010). Field of view effects on pilot performance in flight. *International Journal of Aviation Psychology*, 20, 197-219.
- Cowan, N., Day, L., Saults, J. S., Kellar, T. A., Johnson, T., & Flores, L. (1992). The role of verbal output time in the effects of word- length on immediate memory. *Journal of Memory & Language*, 31, 1-17.
- Creem-Regehr, S. H., Willemsen, P., Gooch, A. A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual environments. *Perception* 34, 191–204.
- Curci, A., Lanciano, T., Soletti, E., & Rime, B. (2013). Negative emotional experiences arouse rumination and affect working memory capacity. *Emotion*, 13, 867-880.
- D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M.

- (1995). The neural basis of the central executive system of working memory. *Nature*, 378, 279-281.
- Della Sala, S., Logie, R. H. (2002). Working Memory. *Encyclopedia of Human Brain*, Volume 4, 819-830.
- De Renzi, E., & Nichelli, P. (1975). Verbal and non-verbal short-term memory impairment following hemispheric damage, *Cortex*, 11, 341–354.
- Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual task investigation. *Journal of Memory and Language*, 48, 148–168.
- Estock, J. L., Alexander, A. L., Stelzer, E. M., & Baughman, K. (2007). Impact of simulator fidelity on F-16 pilot performance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (pp. 75-79). Santa Monica, CA: HFES.
- Fortenbaugh, F., Hicks, J., Hao, L., & Turano, K. (2007). Losing sight of the bigger picture: Peripheral field loss compresses representations of space. *Vision Research*, 47, 2506-2520.
- Gallimore, J. J., Brannon, N. G., & Patterson F. R. (1998). The effects of field-of-view on pilot head movement during low level flight. In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, Chicago, IL (pp. 6-10).
- Garavan, H., Ross, T. J., Li, S. J., & Stein, E. A. (2000). A parametric manipulation of central executive functioning. *Cerebral Cortex*, 10, 585-592.
- Garden, S., Cornoldi, C., & Logie, R. H. (2002). Visuo-spatial working memory in navigation. *Applied Cognitive Psychology*, 16, 35-50.
- Gauthier, M. S., Parush, A., Macuda, T., Tang, D., Craig, G., & Jennings, S. (2008). The

- impact of night vision goggles on way-finding performance and the acquisition of spatial knowledge. *Human Factors*, 50, 311-321.
- Gibbs, P., Hughes, P. K., Meehan, J. W., & Clark, B. (1996). Preliminary study of field-of-view restriction effects on a simulated pursuit flying task. *SimTecT 96 Proceedings* (pp. 269-274). The SimTecT Organizing Committee, Melbourne.
- Guterman, P. S., Allison, R. S., Jennings, S., Craig, G., Parush, A., Gauthier, M., & Macuda, T. (2009). The outer limits: How limiting the field of view impacts navigation and spatial memory. *Journal of Vision*, 9, 1137.
- Henry, L. A., & Botting, N. (2016). Working memory and developmental language impairments. *Child Language, Teaching & Therapy*. Advance Online Publication.
- Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends in Cognitive Sciences*, 3, 174–180.
- Jahanshahi M., Saleem T., Ho A. K., Dirnberger G., & Fuller R. (2006). Random number generation as an index of controlled processing. *Neuropsychology*, 20, 391–399.
- Jansen, S. E. M., Toet, A., & Delleman, N. J. (2010). Restricting the vertical and horizontal extent of the field-of-view: Effects on manoeuvring performance. *The Ergonomics Open Journal*, 3, 19-24.
- Jarmasz, J., & Hollands, J. G. (2009). Confidence intervals in repeated-measures designs: The number of observations principle. *Canadian Journal of Experimental Psychology*, 63, 124-138.
- Jennings S., & Craig G. (2000). Effects of field-of-view on pilot performance in night

- vision goggles flight trials: Preliminary findings. Helmet- and Head Mounted Displays *V*, SPIE Vol. 402 I, Orlando, Florida.
- Johannsdottir, K. R., & Herdman, C. M. (2010). The role of working memory in supporting drivers' situation awareness for surrounding traffic. *Human Factors*, 52, 663-673.
- Kane, M. J., Bleckley, M. K., Conway, A. R., & Engle R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, 130, 169-183.
- Kasper, E., Haworth, L. A., Szoboszlay, Z. P., King, R. D., & Halmos Z. L. (1997). Effects of in-flight field-of-view restriction on rotorcraft pilot head movement. In R. J. Lewandowski, L. A Haworth, & J. J. Girolamo (Eds), *Head-mounted Displays II* (SPIE-2465) (pp. 34-45). Bellingham, WA: The International society for Optical Engineering.
- Knapp, J. M., & Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators Virtual Environments*, 13, 572-577.
- Kruk, R., & Runnings, D. (1989). Low-level flight performance and air combat maneuvering performance in a simulator with a fiber optic head mounted display system. *Proceedings of the American Institute of Aeronautics and Astronautics Conference* (pp. 1989-1992). Bethesda, MD: The IMAGE Society.
- Leibowitz, H., Shupert, C. L., & Post, R. B. (1984). The two modes of visual processing: Implications for spatial orientation. In *Peripheral Vision Horizon Displays (PVHD)*, NASA Conference Publication 2306 (pp. 41-44). Dryden Flight

- Research Facility, NASA Ames Research Center, Edwards Air Force Base, CA.
- Logie, R. H. (1995). *Visuo-spatial working memory*. Hove: Lawrence Erlbaum Associates.
- Logie, R. H., & Pearson, D. G. (1997). The inner eye and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology*, 9(3), 241-257.
- Logie R. H., Della Sala S., Wynn V., & Baddeley A. D. (2000). Visual similarity effects in immediate serial recall. *Quarterly Journal of Experimental Psychology*, 53, 626-646.
- Loomis, J. M., & Knapp, J. M. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger and M. W. Haas (Eds.), *Virtual and adaptive environments* (pp. 21–46). Mahwah, NJ: Erlbaum.
- Marini, A., Gentili, C., Molteni, M., & Fabbro, F. (2014). Differential verbal working memory effects on linguistic production in children with Specific Language Impairment. *Research in Developmental Disabilities*, 35, 3534-3542.
- Martens, M. H., & van Winsum, W. (2000). Measuring distraction: the peripheral detection task. Soesterberg, Netherlands: TNO Human Factors.
- Martoni, R. M., Salgari, G., Galimberi, E., Cavallini, M. C., & O'Neill, J. (2015). Effects of gender and executive function on visuospatial working memory in adult obsessive-compulsive disorder. *European Archives of Psychiatry and Clinical Neuroscience*, 265, 707-718.
- Meneghetti, C., De Beni, R., Gyselinck, V., & Pazzaglia, F. (2013). The joint role of

- spatial ability and imagery strategy in sustaining the learning of spatial descriptions under spatial interference. *Learning and Individual Differences*, 24, 32-41.
- Milner, A. D. & Goodale, M. A. (1993). Visual pathways to perception and action. In T. P. Hicks, S. Molotchukoff, & T. Ono (Eds.) *Progress in Brain Research*, Vol. 95 (pp. 317- 337). Amsterdam: Elsevier.
- Nairne, J. S., Neath, I., & Serra, M. (1997). Proactive interference plays a role in the word-length effect. *Psychonomic Bulletin & Review*, 4, 541-545.
- Niall, K. K., Reising, J. D., & Martin, E. L. (1999). Distance estimation with night vision goggles: A little feedback goes a long way. *Human Factors*, 41, 507-510.
- Oliva, A. (2005). Gist of the scene. In: Itti, L., Rees, G. and Tsotsos, J.K. (Eds.), *Neurobiology of Attention*. Elsevier, San Diego, CA, pp. 251–256.
- Olsson, S., & Burns, P. (2000). *Measuring distraction with a peripheral detection task*. On-line paper. NHTSA Internet Distraction Forum. Available at www.nrd.nhtsa.dot.gov/departments/nrd-13/driver-distraction/welcome.htm.
- Otsuka, Y., & Osaka, N. (2015). High-performers use the phonological loop less to process mental arithmetic during working memory tasks. *The Quarterly Journal of Experimental Psychology*, 68, 878 – 886.
- Patten, C., Kircher, A., Östlund, J., Nilsson, L., & Svensson, O. (2006). Driver experience and cognitive workload in different traffic environments. *Accident Analysis & Prevention*, 38, 887-894.
- Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory*, 2, 509–522.

- Repovs, G., & Baddeley, A. D. (2006). Multi-component model of working memory: explorations in experimental cognitive psychology. *Neuroscience Special Issue, 139*, 5-21.
- Robbins, T. W., Anderson, E. J., Barker, D. R., Bradley, A. C., Fearnlyhough, C., Henson, R., Hudson, S. R., & Baddeley, A. D. (1996). Working memory in chess. *Memory and Cognition, 24*, 83-93.
- Sandor, P. B., & Leger, A. (1991). Tracking with a restricted field of view: Performance and eye-head coordination aspects. *Aviation, Space, and Environmental Medicine, 62*, 1026-1031.
- Sekuler, R., & Ball, K. (1986). Visual localization: age and practice. *Journal of the Optical Society of America. A, Optics and Image Science, 3*, 864-867.
- Sekuler, A. B., Bennett, P. J., & Mamelak, M. (2000). Effects of aging on useful field of view. *Experimental Aging Research, 26*, 103-120.
- Szoboszlay, Z. P., Haworth, L. A., Reynolds, T. L., Lee, A., & Halmos, Z. (1995). Effects of field-of-view restriction on rotorcraft pilot workload and performance: Preliminary results. In R. J. Lewandowski, W. Stephens, & L. A. Haworth (Eds.), *Helmet- and head-mounted displays and symbology design requirements II* (pp. 142-153) (SPIE-2465) Bellingham, WA: The International Society for Optical Engineering.
- Thompson, W. B., Willemsen, P., Gooch, A. A., Creem-Regehr, S. H., Loomis, J. M., & Beall, A., C. (2004). Does the quality of the computer graphics matter when judging distances in visually immersive environments? *Presence: Teleoperators Virtual Environment, 13*, 560–571.

- Toet, A., Jansen, S., & Delleman, N. (2007). Effects of field-of-view restrictions on speed and accuracy of manoeuvring. *Perceptual & Motor Skills*, 105, 1245-1256.
- Toet, A., Jansen, S., & Delleman, N. (2008). Effects of field-of-view restrictions on manoeuvring in a 3-D environment. *Ergonomics*, 51, 385-3894.
- Torrens, V., & Yague, E. (2016). The role of phonological working memory in children with SLI. *Language Acquisition*. Advance Online Publication.
- Towse, J.N., & Neil, D. (1998). Analyzing human random generation behavior: A review of methods used and a computer program for describing performance. *Behavior Research Methods, Instruments, & Computers*, 30, 583-591.
- Van der Horst, A. R. A., & Martens, M. H. (2010). The peripheral detection task (PDT): On-line measurement of driver cognitive workload and selective attention. In *Performance Metrics for Assessing Driver Distraction: The Quest for Improved Road Safety*, G. L. Rupp (ed.). Warrendale, PA SAE International: 73-88.
- Vandierendonck, A. & De Vooght, G. (1997). Working memory constraints on linear reasoning with spatial and temporal contents. *Quarterly Journal of Experimental Psychology*, 50, 803-820.
- Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998). Interfering with the central executive by means of a random interval repetition task. *Quarterly Journal of Experimental Psychology*, 51, 197-218.
- Venturino, M., & Kunze, R. J. (1989). Spatial awareness with a helmet-mounted display. *Proceedings of the Human Factors Society 32nd Annual Meeting*, 1388-1391.
- Venturino, M., & Wells, M. J. (1990). Head movements as a function of field-of-view size on a helmet-mounted display. *Proceedings of the Human Factors*

Society 34th Annual Meeting, 1572-1576.

- Warring, R., Eadie, P., Rickard Liow, S., & Dodd, B. (2016). Do children with phonological short-term and phonological working memory deficits? *Child Language, Teaching & Therapy*. Advance Online Publication.
- Wells, M. J., & Venturino, M. (1990). Performance and head movements using a helmet-mounted display with different sized fields of view. *Optical Engineering*, 29, 870-877.
- Wells, M. J., Venturino, M., & Osgood, R. K. (1988). Using target replacement performance to measure spatial awareness in a helmet-mounted simulator. *Proceedings of the Human Factors Society 32nd Annual Meeting*, 1429-1433.
- Witmer, B. G. & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence: Teleoperators and Virtual Environments*, 7, 144-167.
- Wickens, C. D., Thomas, L. C., & Young, R. B. (2000). Frames of reference for the display of battlefield information: Judgment-display dependencies. *Human Factors*, 42, 660- 675.
- Willemsen, P., Colton, M., Creem-Regehr, S., & Thompson, W. (2009). The effects of head-mounted display mechanical properties and field of view on distance judgments in virtual environments. *ACM Transactions on Applied Perception*, 6, 1-14.
- Winterbottom, M., Patterson, R., Covas, C., Rogers, J., & Pierce, B. (2006). Binocular rivalry and attention in helmet-mounted display applications. In *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting* (pp. 2061–2066). Santa Monica, CA: Human Factors and Ergonomics Society.

- Wu, B., Ooi, T., & He, Z. (2004). Perceiving distance accurately by a directional process of integrating ground information. *Nature*, 428, 73-77.
- Yang, T., Gathercole, S. E., & Allen, R. J. (2014). Benefit of enactment over oral repetition of verbal instruction does not require additional working memory during encoding. *Psychonomic Bulletin & Review*, 21, 186–192.