Effects of visual storage and spatial processing on pursuit tracking: Task interference in the cockpit

by

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ABSTRACT

Visual tracking is the ability to visually follow moving targets and often involves pursuit tracking where actions from the body are made in response to visual input from the environment. Visual and pursuit tracking are used in everyday life (e.g., watching a bird fly, catching a ball), and in complex tasks like piloting aircraft (e.g., flying in formation, instrument flight). The present work examines how working memory supports pursuit tracking to better understand what does and does not interfere with pursuit tracking. In two experiments, secondary tasks designed to selectively tap visuospatial storage and processing in working memory were tested for task demands. In the following two experiments participants completed a computer-based pursuit-tracking task paired with secondary visuospatial storage and processing tasks. The secondary processing task interfered with pursuit tracking whereas the secondary storage task did not. Implications for working memory research and for multitasking in the cockpit are discussed.

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INTRODUCTION

Pursuit-motor tracking is a fundamental perceptuomotor ability that involves using information from the environment to direct and monitor the outcome of continuous motor inputs into a system (Wightman & Lintern, 1985). People use pursuit tracking in a range of everyday interactions with the environment from reaching for moving objects to driving a car (e.g., Strayer & Johnson, 2001). Pursuit tracking is also used in more complex situations, such as controlling an aircraft. For example, pilots engage in pursuit tracking when they use information about the position of their aircraft, either from visual cues in the environment or from the instrument panel to guide control inputs such that optimal flight parameters are met. It has been suggested that pursuit tracking utilizes working memory (Baddeley, Grant, Wight, & Thomson, 1975; Logie, Baddeley, Mané, Donchin, & Sheptak, 1989). The objective of the present research was to examine the role of working memory in pursuit tracking, and in doing so, take steps toward a better understanding of how pursuit tracking can be optimized in the cockpit.

There is a range of situations in aviation that require pilots to engage in pursuit tracking. One situation is where visibility is degraded to the extent that pilots are required to rely solely on the use of instruments in the cockpit to control their aircraft.. Aircraft attitude is typically indicated on an instrument with two symbols: a dynamic line representing the horizon, and another line indicating the aircraft. To control attitude, pilots perform a pursuit tracking task in which they make inputs into the flight controls to adjust the aircraft symbology relative to the continuously changing horizon symbology. A similar, but more advanced, technology for controlling an aircraft involves maneuvering through a virtually displayed corridor, called a highway-in-the-sky. A highway-in-the-sky is represented as 3D symbology on the aircraft instrument panel or on a head-up display. In order to keep within this virtual corridor, a pilot makes control inputs to keep a moving symbol of their aircraft within the highway-in-the-sky symbology.

As with simple pursuit tracking tasks in the lab, pilots are usually able to perform other perceptual-cognitive tasks while concurrently controlling their aircraft. However, tasks that are supported by the same spatial processing mechanisms as pursuit tracking may interfere with flight control. Disruption to pursuit tracking has the potential to create hazardous situations in aircraft. Consider flying in formation. Flying in a formation with other aircraft places heavy demands on pursuit tracking because pilots must maintain awareness of the dynamic positions of the other aircraft while making constant adjustments to their own relative position and motion. Interruptions to a pilot's ability to accurately track and respond to visual inputs while in formation flight could result in an air collision.

Another demanding in-flight task that requires continuous and precise pursuit tracking is air-to-air refueling. In this situation pilots are required to align an intake nozzle on their aircraft with the basket of a fueling hose that is trailing from another moving aircraft. For a proper fueling connection to be made, the receiving pilot must maneuver their aircraft to align with the basket and then accurately guide it into place. Failure to accurately track and pursue the movement of the basket for initial contact can result in a negative outcomes ranging in severity from a poor connection (fuel spray) to severe damage to the receiving aircraft leading to a fatal accident.

Pursuit Tracking in Skill Acquisition and Training

Pursuit tracking has been investigated in many lines of research, including military investigations of manual vehicle control (e.g., Wasicko, McRuder and Magdaleno, 1966), executive function in Alzheimer's patients (Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991) and early lab studies of visuospatial working memory

(Baddeley, Grant, Wight, & Thomson, 1975). In these studies pursuit tracking evolved from the pursuit rotor task which involved keeping a pointer on the target of a spinning rotor disc to modern versions of pursuit tracking tasks that involve complex trajectories and digital cursors controlled by a variety of interface devices. After these early visuospatial working memory studies, Logie, Baddeley, Mané, Donchin, et al. (1989) used a video game called Space Fortress (Mané & Donchin, 1989) to investigate the cognitive demands of acquiring perceptuomotor skill. Space Fortress requires that players acquire the perceptuomotor skill needed to maneuver their spaceship within an environment surrounding an enemy fortress (see Figure 1). Maneuvering the spaceship toward bonus items and away from fortress fire with a joystick was a taxing pursuit tracking task requiring substantial perceptuomotor skill. In addition to performing these complex maneuvers, players also need to aim and fire their own rounds at the fortress in order to win. Along with to the task of maneuvering and aiming, players also needed to quickly identify and retrieve bonus items before they expired and to employ high level strategizing in order to plan when to take action on the fortress and when to retrieve items.

In addition to these in-game tasks, Logie et al. (1989) presented a number of secondary tasks during game play for the purpose of investigating the relationship between acquiring perceptuomotor control (pursuit tracking) skills and visuospatial working memory. During early skill acquisition (i.e., before players had become experts at maneuvering the ship) both the visuospatial and the verbal versions of an imagery task

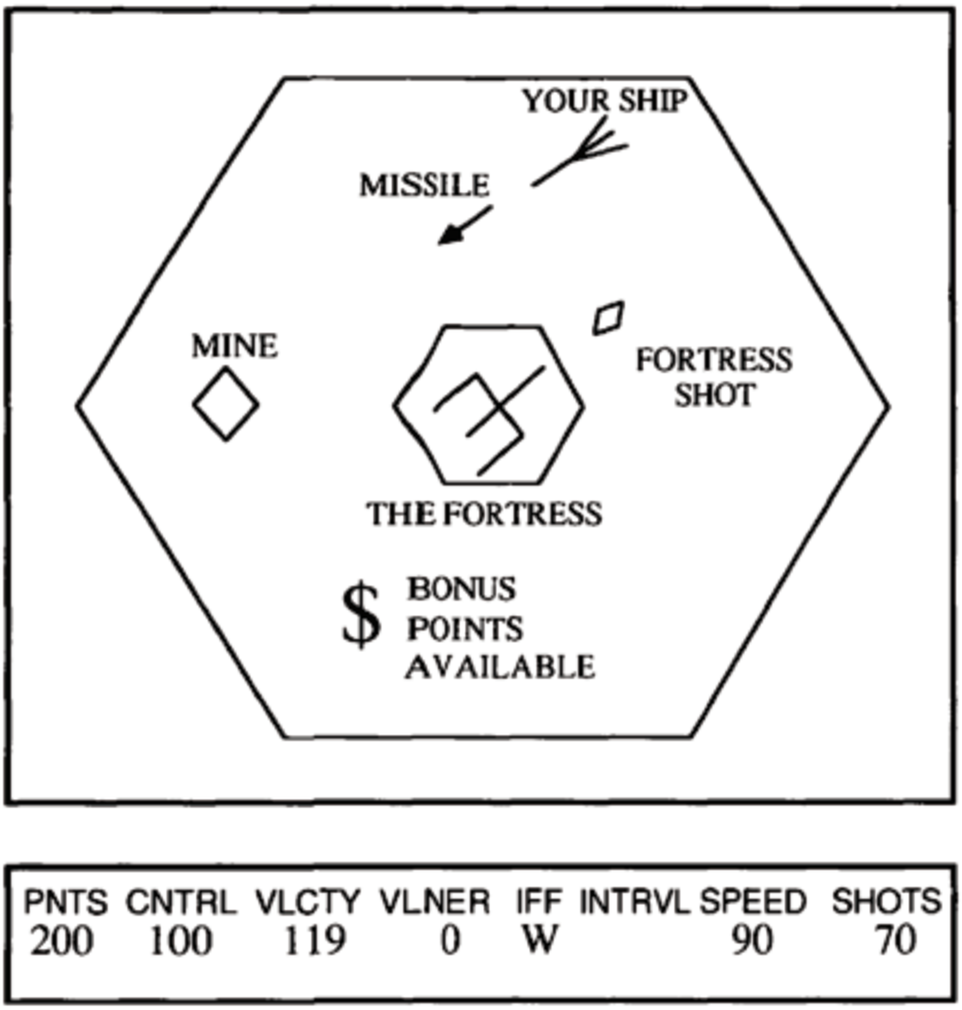

Figure 1. Modified version of the Space Fortress game (Mané & Donchin, 1989) as it was displayed to student pilots in Gopher et al., 1994.

called the Brooks matrix task (discussed at in the next section) interfered with participants' ability to control their ship and aim at the target. However, once participants gained the expertise required to maneuver the ship, only the visuospatial version of the Brooks matrix task interfered with controlling the ship and aiming. This finding was interpreted as evidence that demanding pursuit tracking tasks such as those involved in playing Space Fortress may initially place high demand on general cognitive resources, but once the perceptuomotor skills are mastered, pursuit tracking is a task that requires mainly visuospatial working memory.

Gopher, Weil, and Bareket (1994) used a modified version of Space Fortress to investigate its potential for in-flight training (see Figure 3). Two groups of flight students were matched for potential flight ability and in-flight training hours. Flight instructors rated the in-flight performance of students who played Space Fortress as significantly better than the performance of a control group of flight students with no game experience. Gopher et al. argued that two factors led to the game group outperforming their peers. The first is the expertise in attentional control, or 'multitasking', that student pilots gained while playing Space Fortress. Indeed research has demonstrated a positive transfer of low level cognitive skills like dividing attention from video games to attention tasks in the lab (Green & Bavelier, 2004). It has also been suggested that mastering action video games improves an individual's ability to make probabilistic inferences based on sequences of events both in and out of the game setting (Green, Pouget, & Bavelier, 2010). As such, those students who played Space Fortress were more practiced in the skills that allow them to manage the numerous tasks required to fly their aircraft than the control group students.

Gopher et al. also suggested that it was the similarity of the display and controls of Space Fortress to real flight displays and flight controls that allowed the group with Space Fortress experience to outperform their peers in flight. Indeed, as Gopher et al. pointed out, a similar set of skills is required to play Space Fortress as those required to operate an aircraft. The operation of an aircraft requires continuous manual control (pursuit tracking), visuospatial orientation (spatial processing), a combination of long and short-term memory (visual storage), and attentional shifting. In summary, the cognitive and perceptuomotor skills required to control an on-screen avatar through a series of maneuvers is directly related to individual's ability to learn to maneuver an aircraft.

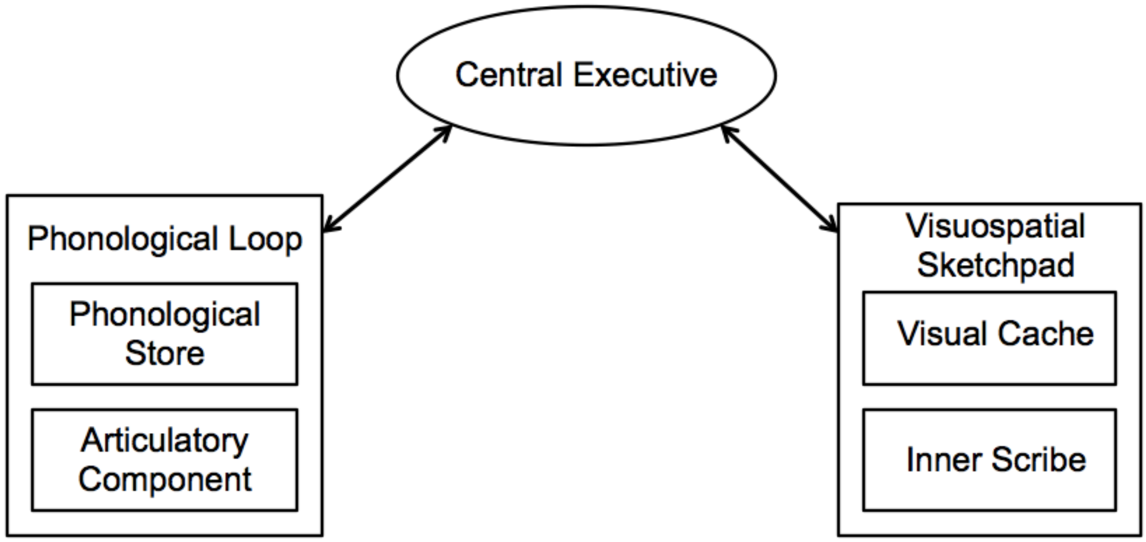

Figure 2. Multiple component model of working memory from Baddeley & Hitch (1974) with Logie's (1995) fractionation of the visuospatial sketchpad into the Visual Cache and Inner Scribe also depicted.

Working Memory

Working memory is a form of short-term memory storage that is characterized by its ability to manipulate (i.e., "work" on) information that it currently holds (Baddeley & Hitch, 1974; Baddeley & Hitch, 1994; Conway, Kane, Bunting, Hambrick, Wilhelm, & Engle, 2001; Logie, 1955, 2011). Although there are many conceptualizations of working memory (e.g., Cowan, 1995; Barrouillet, Bernadin & Camos, 2004; Engle, Tuholski, Laughlin, Conway, 1999) the current work used Baddeley and Hitch's (1974) multiple component model of working memory as a framework. The multiple component model includes 3 components: a Central Executive to allocate attentional processing resources and control response selection and inhibition, and 2 slave systems dedicated to the storage and processing of phonological and visual information (see Figure 2). The Central Executive is implicated in task switching, where cognitive resources may need to be shifted within and between the working memory slave systems to complete different cognitive tasks. The Phonological Loop is a slave system used for the temporary storage and manipulation phonological information, whereas the Visuospatial Sketchpad is a slave system used for the temporary storage and manipulation of visuospatial information.

There is a large body of evidence supporting a distinction within the Phonological Loop between a storage mechanism where phonological codes are temporarily stored and an articulatory component where phonological codes are reactivated (Baddeley, 2001, 2012; Baddeley & Hitch, 1974, 1994; Logie, 1995). Support for this distinction between storage and rehearsal mechanisms comes from a number of effects on verbal item recall. One such effect is the phonological similarity effect, where similar sounding words (e.g., cat, hat, bat) are more difficult to temporarily store than dissimilar sounding words (e.g., car, pot, bun). This effect is exclusive to similar sounding phonological items, but not to those similar in orthography or meaning (Baddeley, 1966). Further evidence comes from the word length effect, where longer words (e.g., alligator, elephant, rhinoceros) are more difficult to store than shorter words (e.g., bird, dog, horse). The phonological similarity effect and the word length effect both point to the storage of phonological information being maintained via subvocal rehearsal in the phonological loop at a dedicated rehearsal mechanism. Critically, if this articulatory component is loaded with the task of repeating words or sounds, either vocally or subvocally (e.g., “the”, “the”, “the”), subsequent recall for longer versus shorter words becomes equal (Baddeley, Thompson, & Buchanan, 1975). Thus when the passive phonological store is left without aid from articulatory rehearsal, phonological information can be temporarily stored, but it decays quickly. This evidence supports the existence of a distinct component for actively rehearsing (*processing*) phonological information – the articulatory loop - and one for temporarily and passively *storing* phonological information – the phonological store.

Compared to the phonological loop, the visuospatial sketchpad has received fairly little experimental investigation. For this reason the architecture of the visuospatial sketchpad is not well defined. Logie (1995) suggested that, like the phonological loop, the visuospatial sketchpad consists of separate subcomponents for storage and processing: the visual cache and the inner scribe, respectively. There is evidence that visual characteristics such as form and colour are temporarily maintained in the visual cache, and the inner scribe is responsible for actively refreshing dynamic information such as spatial relationships and motion (Logie, 1995; Pickering, Gathercole, Hall, et al., 2001).

Investigation of a possible fractionation of the visuospatial sketchpad began with a focus on distinguishing between *visual* versus *spatial* domains within the visuospatial sketchpad. Before reviewing this evidence it should be noted that the focus of the current work departs from the tradition of delineating visual and spatial contributions to visuospatial working memory, but instead examines the distinction between storage and processing components in the visuospatial sketchpad. That said, there are direct parallels between these two avenues of exploration. Insofar as the visual cache *stores* information regarding form and colour (i.e., *visual* information), it can be described primarily as a storage component in the visuospatial sketchpad. Similarly, the inner scribe, which *processes* dynamic information pertaining to movement and locational relationships is often described as *spatial* in nature can be described primarily as a component *processes* information in the visuospatial sketchpad (Logie, 1995). There is evidence that this spatial processing component does not receive inputs from visual information (Baddeley & Lieberman, 1980) and can be described as a general spatial processing unit in the Visuospatial Sketchpad.

Evidence for Fractionation of the Visuospatial Sketchpad

When opening the investigation into visuospatial working memory, Baddeley began with an inherently spatial auditory pursuit tracking task (see Baddeley & Lieberman, 1980) and concluded that the visuospatial slave system of working memory was inherently spatial, and not visual, in nature. However, the tasked Baddeley and Lieberman used lacked the power to detect any interruption to visual working memory. To address this shortfall in the literature, Logie (1986) devised an experimental paradigm that taxed the visual component of working memory's visuospatial slave system. In the experiment, participants were asked to recall a word list that could be retained using either a visual mnemonic mechanism (visual peg-word method) or a verbal rote mechanism (verbal working memory). The visual peg-word method required that participants memorize a list of rhyming number-item word pairs such as one-bun, two-shoe, three-tree, and so on up to ten. Participants were then given a list of words that was to be linked to the visual mnemonic from the peg-word list (e.g., "one-car, two-pin). From here participants were instructed to mentally visualize the stimulus word with the visual peg-word mnemonic, such as a bun driving a car and a shoe full of pins. At recall participants were presented with the number probe and were asked to recall the image they created (e.g., a bun driving a car) and then the stimulus word ("car").

For the verbal condition, participants were asked to cumulatively rehearse the words in their mind as the list grew. This meant that in the verbal condition the list was retained via verbal working memory. For example, the list might be repeated mentally as 'cat, cat, cat, door, cat, door, cat door, phone, cat, door, phone…' and so forth until the end of the list. Like in the visual condition, participant were probed with a number and asked to recall the word that corresponded with that numeric position in the list (e.g. the second word in the list was "door"). During the retention interval when participants were rehearsing the word lists they were presented with visually stimuli (irrelevant line drawings of objects and animals or matrix patterns) and verbal stimuli (irrelevant speech sounds, the names of the objects and animals in the drawings). It was found that the presentation of irrelevant line drawings and matrix patterns during the retention interval selectively interfered with recall for visually encoded (peg-word) word list while the presentation of irrelevant speech stimuli selectively interfered with verbally encoded word list. Because the interference stimuli were purely visual and the visuospatial working memory task itself relied on mental visualization, Logie concluded that the visuospatial counterpart to verbal working memory must be inherently visual rather than spatial.

More recent studies have shown that Logie's (1986) conclusion that the visuospatial sketchpad is visual rather than spatial may have been premature (e.g., Della Sala et al., 1999; Logie & Marchetti, 1991). Rather, it appears that the visuospatial sketchpad relies on both visual and spatial informational codes. To illustrate this, Logie and Marchetti (1991) asked participants to perform a visual storage task involving sequences of colours and a spatial memory task involving sequences of screen locations. In both conditions, a sequence of stimuli (either a series of colour patches at the centre of the screen or a series of dot locations) would be presented, followed by a 10 s retention interval, after which participants were asked to recall the target sequence. Three conditions were presented during the retention interval including a control condition where participants only had to remember the stimuli sequences. In the visual interference condition, irrelevant black and white line drawings were displayed during the retention interval. In the spatial interference condition participants performed an arm movement task where they were asked to point through a sequence of cells in an empty matrix taped to a nearby table. The borders of the matrix cells were created by layering enough tape on the table to provide a haptic cue, and participants were asked to point one cell at a time while both the matrix and their hand were covered from view. This ensured that there was no visual contribution in the spatial interference task. The recall of colour sequence information was selectively disrupted by the line drawings whereas the arm movement task selectively interfered with screen location sequences. This crossed double dissociation pattern led Logie and Marchetti to conclude that there was indeed a distinction between visual and spatial working memory. This finding was replicated by Della Sala et al. (1999) who found the same interference patterns when these interference tasks were presented during a visual pattern recognition task and a location sequence (Corsi block) task.

The double dissociation between visual storage and spatial processing has been replicated by many other researchers (see Klauer & Zhao, 2004 for a review), which has led to the currently accepted view that there are separate visual and spatial subcomponents within the visuospatial sketchpad. Klauer and Zhao (2004) reviewed numerous studies replicating the interference patterns described above by using a variety of intervening visual and spatial tasks. In many of these studies, the primary visual memory task stimuli were sequences of arrows, images of everyday objects, or images of irregular polygons. The primary spatial tasks used location-based memory paradigms including *n*-back tasks where participants were required to recall the locations of stimuli presented *n* stimuli before the current stimulus. The secondary tasks used to create visual interference usually consisted of line drawings, colour flickers and size estimation tasks, while spatial interference was induced using spatial tapping tasks, movement judgments and location-based distractors.

Despite the general consistency between these studies, Klauer and Zhao (2004) cautioned that many of them had methodological concerns, not the least of which was the difference in task difficulty between the visual and spatial tasks. For example, Della Sala et al.'s (1999) procedure required that participants recall only a single visual pattern per trial while the Corsi task required that they recall and point to a sequence of blocks in order. This could in fact highlight difference in static versus dynamic visuospatial working memory rather than visual versus spatial working memory (Pickering et al., 2001). Another noted concern was the differential requirements of the interference (secondary) tasks. In many of the reviewed studies, the visual interference task often required passively viewing a visual distracter (e.g., line drawings) while the spatial interference task required active spatial tapping (e.g., Della Sala et al., 1999; Logie & Marchetti, 1991). It could be the case that interference patterns between visual and spatial working memory are confounded by the difference between passive versus active interference tasks, where the locus of interference could be the increased cognitive recourses required to perform active tasks. Further, none of the studies reviewed by Klauer and Zhao (2004) reported performance on the secondary tasks and only few of them addressed the potential for verbal memory contributions during recall. Without controlling for verbal contributions, it is possible that participants relied on information that was recoded into verbal working memory resulting in an impure measure of visual working memory.

To address these concerns, Klauer and Zhao (2004) developed primary visual and spatial memory tasks that required active (rather than passive) processing and equated these tasks for difficulty. The primary visual task required participants to recall a previously presented Chinese ideograph after a 10 s retention interval, whereas participants were to recall the location of a dot after a 10 s retention interval in the spatial task. Both tasks required that participants retain only one item for subsequent recognition from a choice set. During the retention interval, participants were presented with no stimuli (control), a colour judgment task (visual), or a movement discrimination task (spatial). The colour judgment task required participants to discriminate between red and blue hues, where half of the hues presented were a variant shade of red and the other half a variant shade of blue. The movement discrimination task presented 12 asterisks on the computer screen where all but one were moving and participants were to quickly click on the stationary asterisk. Klauer and Zhao reported that the visual interference condition (colour judgment task) selectively disrupted recall of the Chinese ideographs while dot locations were unaffected, with the reverse found for the spatial interference condition (asterisk movement task). Further, the secondary task performance did not differ significantly between primary task conditions. If for example, performance on the spatial interference task (asterisk movement task) had been significantly poorer in the primary visual task (memory for sequence of colours) condition than the primary spatial task (memory for sequences of locations) then it is possible that the effect was not interference between visual and spatial domains of working memory but due to shifted allocation of processing resources. Subsequent experiments by Klauer and Zhao in which the retention interval and the Chinese ideograph set were manipulated and articulatory suppression was introduced confirmed the distinct presence of selective interference between visual versus spatial working memory tasks.

A double dissociation between visual and spatial processing in working memory has also been demonstrated in neurological patients with different cognitive impairments for visual and spatial processing (Della Sala et al., 1999; Smith & Jonides, 1997). Lesion patients with impaired visual information processing perform as well as healthy controls on spatial tasks, while the reverse pattern has been observed in different groups of lesion patients. Positron Emission Tomography (PET) imaging studies have highlighted neuroanatomical distinctions between spatial and visual memory, where spatial memory appears to be lateralized to the right hemisphere and visual (along with verbal) memory are lateralized to the left hemisphere (Smith & Jonides, 1997). Although there is clearer evidence for separate neural circuitry for the passive storage and active rehearsal for phonological information in working memory, there is some indication (see Smith &

Jonides, 1997) that this division of neurological circuitry also exists for spatial information. It should be noted, however, that the distinction between visual and spatial working memory used here was relatively lax, especially when compared to the cognitive behavioural studies reviewed above.

Taken together, the studies reviewed in this section provide behavioural and neurological evidence that visual and spatial working memory are separate processes that unfold in two separate subsystems: a visual cache for the temporary storage of visual information and an inner scribe that processes spatial information. Although it is still unclear how the inner scribe "rehearses" information, it is generally agreed that processing at the inner scribe consists of updating dynamic spatial information such as the spatial relationships between objects, pathways between them, and controlling intentional movements (Logie, 1995; Pickering, Gathercole, Hall, & Lloyd, 2001; Quinn & Ralston, 1986; Salaway & Logie, 1995). As such, a task that relies on the ability to process information about the spatial relationships between objects and their relative motion, such as pursuit tracking, could be considered a pure spatial processing task.

Pursuit Tracking as a Spatial Working Memory Task

Early investigations of pursuit tracking and working memory began before there was a clear distinction between visual and spatial working memory. Thus most of this early work using pursuit tracking has been focused on the examining the distinction between visual and verbal working memory. Research on how working memory supports visual pursuit tracking began shortly after Baddeley and Hitch (1974) developed the classic working memory framework. Baddeley, Grant, Wight, and Thomson (1975) asked participants to perform to track a target using a pursuit rotor task (an early version of the pursuit tracking task) while simultaneously, performing Brooks' (1968) matrix task. In the Brooks matrix task, participants mentally populate the cells of an empty matrix with

	2	4
	3	7

Figure 3. Example of mentally constructed Brooks matrix using the verbal instructions: "Start at the cell one down from the top, and one left from the edge of the matrix, place a 2 here. Move one cell to the right, place a 4 here. Move one cell down, place a 7 here, move one cell to the left, place a 3 here."

numbers given to them in verbal instructions. For example, a 3x3 matrix may be used, and participants would be given verbal instructions to constructed a mental image of the matrix (see Figure 3), and used this to aid in recalling the verbal instructions later.

This version of the Brooks matrix task has been used extensively in the literature to investigate mental imagery and visuospatial working memory (e.g., Baddeley et al., 1975; Baddeley & Lieberman, 1980; Quinn & Ralston, 1986; Quinn, 1991). In a verbal version of the Brooks matrix task, the directional words in the instructions were replaced with irrelevant words that need to be memorized in verbal memory. For example, the above instructions would become:

"Start at the cell one down from the top, and one left from the edge of the matrix, place a 2 here. Move one cell to the *good*, place a 4 here. move one cell *slow*, place a 7 here, move one cell to the *bad*, place a 3 here"

Here, participants were unable to create a mental image of a matrix to aid them when recalling the verbal instructions. Baddeley et al. (1975) found the pursuit rotor task selectively interfered with the recall of the instructions in the spatial condition of the Brooks matrix task (direction words used), but not in the verbal condition (irrelevant words used). Thus, even at this early stage in working memory research, there was strong evidence for the distinction between verbal and visuospatial working memory.

Baddeley and Lieberman (1980) revisited visuospatial working memory, but this time using an auditory tracking task instead of a visual (pursuit) tracking task. Blindfolded participants were asked to use a flashlight to point to a swinging pendulum, which gave an auditory cue when participants were on target. Once again, participants were to simultaneously complete the spatial and the verbal versions of the Brooks matrix task. Baddeley and Lieberman found that even this auditory version of pursuit tracking interfered with the spatial Brooks matrix task, but not its verbal counterpart. This finding provided converging evidence that pursuit tracking is a relatively pure spatial (rather than visual) task. Shortly thereafter, researchers began to isolate and examine the action components of pursuit tracking in spatial working memory.

Quinn and Ralston (1986) used the Brooks matrix task to investigate the influence of arm movements on visuospatial working memory. While performing the spatial version of the Brooks matrix task, participants pointed at the cells of an unseen matrix, which was also used by Logie and Marchetti (1991; described above). Quinn and Ralston had participants make arm movements in blocked conditions: compatible, incompatible, and no movement. In the compatible condition, participants made movements that corresponded to the verbal instructions for the Brooks matrix task. For example, if the Brooks matrix instructions were to move down one cell and left one cell, participants would make arm/hand movements such that their finger would move through the appropriate cells of the matrix in time with the instructions. In the incompatible condition, participants were to follow a predetermined pattern in time with the instructions, regardless of the directions provided in the instructions. There were no arm/hand movements in the control condition. Compatible arm movements did not interfere with recall for the spatial instructions given in the Brooks matrix task while incompatible movements did interfere. Interference on the Brooks matrix task also occurred when the experimenter moved participants' arms passively (Quinn, 1991). However, interference only occurred when participants anticipated the passive arm movements. The finding that controlling, or even anticipating, arm/hand movement interferes with the Brooks matrix task suggests that the interference from pursuit tracking found by Baddeley and colleagues (1975; 1980) was caused by the action component of pursuit tracking.

When coupled with the evidence that spatial tapping tasks interfere with spatial processing tasks, but not visual storage tasks (Della Sala et al., 1999; Logie & Marchetti, 1991), these findings point to the conclusion that the control of movement interferes with the maintenance (processing) of other spatial information. For this reason tasks that involve the generation or processing of movement or pathways between objects are thought to be carried out at the inner scribe of visuospatial working memory (Logie, 1995; Pickering, Gathercole, Hall, & Lloyd, 2001; Quinn & Ralston, 1986; Salaway & Logie, 1995). It is not difficult to imagine a scenario in the cockpit where, for example, a pilot may be actively engaged in maintaining flight formation with continuous manual inputs (pursuit tracking) while estimating distances between other aircraft, judging aircraft attitude from the represented wings on the attitude indicator, or any number of other tasks requiring a pilot to process spatial relationships or movement.

Present Research

The experiments reported in this thesis involved a pursuit-tracking task in which participants used a game controller to pursue a moving target on a computer screen. Participants performed pursuit tracking concurrently with a visual storage task or a spatial processing task. The storage and processing task stimuli were embedded within the pursuit tracking target such that participants were able to view the pursuit tracking and storage/processing stimuli at the same time. This novel approach of combining the pursuit tracking and storage/processing task stimuli into one entity provided a true dual-task paradigm for investigating the effects of visual storage and spatial processing on pursuit tracking.

To date, there has not been a dual-task experiment involving visual and spatial stimuli where the two tasks occurred simultaneously. Most studies involve interruptions to the primary visual storage or spatial processing task using an intervening task during which the primary task information must be held in short or long term memory, depending on the length of the intervening task (e.g., Logie & Marchetti, 1991; Della Sala et al., 1999). The exception is the early work on visuospatial working memory that involved various forms of pursuit tracking (Baddeley et al. 1975; Baddeley & Lieberman, 1980; Logie et al., 1989) combined with verbal and spatial tasks such as the Brooks matrix task. These studies provided strong evidence of distinct verbal and visuospatial working memory subsystems. The present research examined and differentiated between visual storage and spatial processing within the visuospatial working memory subsystem.

The majority of work investigating spatial working memory in has relied heavily on sequential recall of stimulus locations (Della Sala et al., 1999; Logie & Marchetti, 1991), word lists (Logie, 1986) and the Brooks matrix task (e.g., Baddeley & Lieberman, 1980), all of which tap the ability to temporarily store information. Even with evidence for distinct visual storage and spatial processing components, studies continued to use spatial processing tasks that taxed the ability to temporarily store sequenced information (see Klauer and Zhao, 2004). Therefore, it is difficult to determine whether the reported effects are truly reflecting an interruption to spatial processing, or whether the effects reflect an interruption to the storage required to perform these spatial tasks. With evidence that remembering and generating movements selectively interferes with spatial rather than visual tasks (e.g., Della Sala et al., 1999; Logie & Marchetti, 1991; Quinn & Ralston, 1986), it follows that pursuit tracking is an excellent task for tapping the inner scribe of visuospatial working memory. Pursuit tracking as a relatively pure spatial processing task has yet to be paired with similarly pure visual storage and spatial processing tasks.

The spatial processing task used in the present research was developed so as to not place any demand on visual storage and can be described as a low-level version of pursuit tracking. In this spatial processing task, participants were required to follow and respond to changes in the direction of motion of a single dot located within the pursuit tracking target grid (see Figure 3). In order to accurately follow the motion of the dot, participants needed to use the same cognitive mechanisms required to follow and pursue a moving target in a standard pursuit tracking task. Therefore, the primary pursuit tracking task and the secondary spatial processing task were assumed to both tax the visuospatial sketchpad's inner scribe.

In contrast, the visual storage task used in the present research follows a typical visual memory task. Participants were asked to visually inspect and encode a visual matrix pattern and compare it to a second pattern after a brief retention interval. As with the spatial processing task, the stimuli for the visual storage task were presented within the pursuit tracking target grid. Given that only visual memory is required to retain the pattern, the matrix matching task is assumed to selectively tax visual storage in the visual cache of the visuospatial sketchpad. In sum, the experiments reported here separately combined a pure visual storage task and a pure spatial processing task with pursuit tracking. It was hypothesized that pursuit tracking performance would suffer when combined with the dot motion task (spatial processing) but would remain intact when combined with the matrix matching task (visual storage). It was further hypothesized that pursuit tracking would have a greater impact on the dot motion task than on the matrix matching task, compared to when these two secondary tasks were performed in isolation.

Overview of Experiments

Four experiments are reported. Experiment 1 was a preliminary investigation to determine whether it was feasible to have participants perform the full planned experiment (Experiment 3). Experiment 2 was conducted to equate the difficulty of the concurrent visual storage and spatial processing tasks proposed for Experiment 3. This ensured that any patterns of interference observed in Experiment 3 could not be attributed to differences in secondary task demand. Experiment 3 examined patterns of interference between pursuit tracking and the visual storage and spatial processing tasks. Experiment 4 explored the influence of executing differential motor commands during the concurrent spatial processing task by simplifying the response paradigm of the secondary spatial processing task.

EXPERIMENT 1

The objective of Experiment 1 was to determine whether people could perform a visual memory task involving moving matrix stimuli. These would serve as the matrix stimuli for the visual storage task in upcoming experiments. Participants' accuracy and response time on a matrix comparison task was compared between blocked static and dynamic conditions.

Method

Participants. Eleven participants with normal or corrected-to-normal vision volunteered to participate.

Design. A one-way design with two levels was used to compare performance on the matrix comparison task between two conditions: a static condition where matrices were displayed centrally, and a dynamic condition where matrices moved across the computer screen.

Materials. A 5 x 5 grid (300x300 px, approximately 6 deg. visual angle) was presented to participants in both the static and dynamic conditions. In the static condition the grid remained at the centre of the screen during all trials. In the dynamic condition the grid followed a pseudorandom figure-8 pattern created by combining sinusoidal functions in the X and Y dimensions and moved at a maximum speed of 300 px/s. In both conditions patterns of dots were presented within the cells of the grid and participant responses were collected using the direction pad on an Xbox 360 controller connected to a Dell XPS computer. The experiment was coded in C++ using OpenGL and SDL libraries and was presented on an Asus V678H 120Hz 27-inch LCD monitor.

Tasks. Participants were asked to perform the same task for the static and dynamic conditions. Each trial began with a randomly selected 2000-4000 ms delay

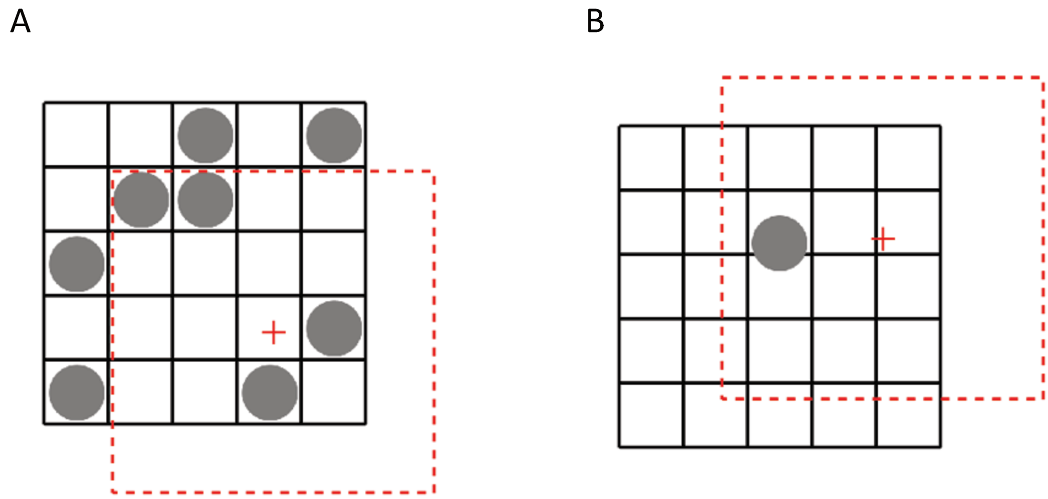

Figure 4. Depictions of the 5x5 tracking target and the red participant-controlled cursor used in the dual-task conditions: Visual storage (A) and Spatial processing (B). In the single-task tracking condition no dots were displayed in the target grid, and in the single-task visual storage and spatial processing conditions no tracking cursor was presented (not depicted).

interval before the first matrix was presented in the grid (see Fig 4A). Participants were instructed to maintain a visual image of the first matrix in their mind by taking a 'mental snapshot'. The first matrix was presented for 1500 ms followed by a 5000 ms retention interval where the grid was left empty. The second matrix was presented for a further 1500 ms at which point participants were asked to respond via button press whether this matrix was the same or different from the first. On half of the trials the dot patterns were identical. On the other half, one dot was moved by one cell. A further 1000 ms response window was included after the second matrix presentation after which the trial terminated.

Procedure. Participants completed a set of 10 practice trials before each 40-trial condition and condition order was counterbalanced such that half of the participants received the static condition before the dynamic condition, and the other half received the reverse order.

	Response Time	Accuracy
Static	869	87
Dynamic	897	85

Table 1: Mean response time (ms) and Accuracy (% correct) for the static and dynamic versions of the visual storage (matrix comparison) task in Experiment 1.

Results

All tests reported were conducted at α=. 05, 2-tailed. Spoiled trials (9% of trials) where no response was made were removed from the analysis. As shown in Table 1, the mean accuracy for matrix comparison responses was not significantly different between the static condition and the dynamic conditions $t(10)= .701$, $p>.05$, . Mean response time, however, was shorter for static displays than for dynamic displays, $t(10)= 2.3$, $p< .05$.

Discussion

Participants' judgments on the matrix comparison task were not more accurate when the matrices were presented statically as compared to when they moved on the computer screen. Similar accuracy performance was interpreted as evidence that adding motion to a matrix match-to-sample task does not add a processing requirement above and beyond those of the original task demands. The finding that participants responded more quickly to static displays than dynamic displays suggests that participants may have traded speed to maintain accuracy in the dynamic condition. This does not compromise the interpretation that these versions of the task are comparable because accuracy remained high in both conditions of the matrix task. Critically, the dynamic matrix task can be used in subsequent experiments to represent visual storage as described in the working memory literature.

EXPERIMENT 2

The objective of Experiment 2 was to equate the difficulty of the secondary visual storage and spatial processing tasks. Because of the difficulty comparing response time and accuracy scores between the visual storage and processing tasks, performance on a simple reaction time secondary task was used to determine if the demands of the visuospatial tasks were comparable.

Method

Participants. Twelve participants with normal or corrected-to-normal vision volunteered to participate. Two participants were removed from the analysis because their performance was at or below chance for one or more of the experimental blocks.

Design*:* A one-way within-subjects design was used with five conditions: single-task tone detection, single-task visual storage, single-task spatial processing, dual task visual storage + tone detection, and dual-task spatial processing + tone detection. Response time and detection rate for tones in the single-task tone detection condition were compared to those in the dual-task visual storage and dual-task spatial processing conditions. Response time and accuracy for each visuospatial task was compared between its single and dual-task conditions.

Materials. The moving grid from Experiment 1 was presented to participants during single-task visuospatial conditions and dual-task conditions. A pattern of dots (storage conditions) or a single moving dot (processing conditions, see *Tasks* below) was displayed within the grid (see Figure 3) and an auditory tone was presented through a set of Harmon Kardon Rev A00 computer speakers.

Tasks. The experiment consisted of three single-task conditions (auditory detection, visual storage, and spatial processing) and two dual-task conditions (visual storage + auditory detection, spatial processing + auditory detection). The five conditions were blocked, each preceded immediately by practice trials. The single-task auditory detection condition was split into 2 blocks that preceded each visuospatial task condition for a total of six experimental blocks. Each single-task auditory detection block consisted of 40 tones, presented over a 3-minute period. Participants were asked to attend to the fixation cross and make a button-press response as soon as they heard a tone.

The remaining four blocks consisted of forty 12-second trials, each of which was initiated by the participant. The single-task visual storage condition was identical to the dynamic condition of Experiment 1. The dual-task visual storage condition was also identical except that participants had to respond to a tone while simultaneously performing the visual storage task.

The spatial processing task was intended to selectively tax spatial processing and not visual storage. In the single-task spatial processing condition, participants were required to monitor the motion of a single dot within the target grid and make an up or down button-press response to indicate the current direction of the dot.. To prevent participants from anticipating a directional change, the dot's movement was not confined to the boundaries of the grid. That is, the dot could change direction after crossing the grid's upper or lower border. The dual-task spatial processing condition was identical to the single-task condition described above, except that participants had to respond to a tone while simultaneously performing the processing task.

Procedure. Participants completed sets of 10 practice trials prior to the visual storage task and 5 practice trials prior to the spatial processing and auditory detection tasks until they attained at least 60% accuracy. The experiment always started with the auditory detection task, followed by one of the single-task visuospatial conditions and then its corresponding dual-task condition.

After completing the single-task and dual-task conditions for one of the visuospatial tasks (e.g., storage), participants would complete the second half of the single-task auditory detection condition followed by the other visuospatial task (e.g., processing) conditions. The order of the visuospatial task conditions was counterbalanced such that half of the participants received the storage condition before the processing condition, with the other half receiving the reverse order.

In the baseline auditory detection blocks, a single fixation cross appeared at the center of the screen while a 700 Hz tone was randomly presented through a set of computer speakers every 3-7 seconds and participants were asked to press the green 'A' button as quickly as possible. The visual storage task followed the same procedure as Experiment 1. In the spatial processing task the dot was stationary for the a randomly chosen interval of 1500–2000 ms at the start of each trial, after which it would begin moving either upwards or downwards for a random interval between 2000–5000 ms at a rate of 55 px/s. The dot would change direction an average of 3 times per trial. Participants had up to 2000ms to respond to a directional change by pressing the 'Up' arrow on the direction pad as soon as they detected that the dot's motion switch to upward, and pressing the 'Down' arrow when they detected downward motion. In both the visuospatial storage and processing tasks, participants had a 2000ms to respond, after which the trial would end and the next would initiate upon participants' press of the right joystick.

Results

Auditory Detection Task

All tests reported were conducted at α=. 05, 2-tailed. Participant responses to random tones were compared between the single-task auditory detection condition and the dual-task visuospatial conditions. Mean response detection rate (see Fig 4) for tones

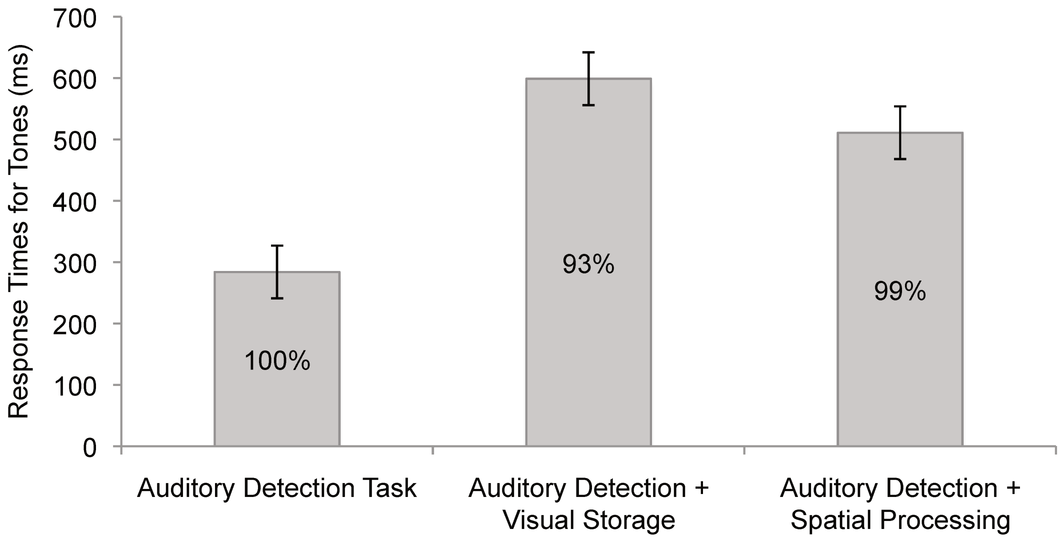

Figure 5: Mean response times (ms) for the auditory detection task in the single-task, dual-task with visual storage, and dual-task with spatial processing conditions. Mean response rate (%) depicted at centre of bar for each condition. Error bars represent 95% confidence intervals according to Jarmasz and Hollands, 2009.

did not differ between the single-task auditory detection condition and the dual-task visual storage condition, $t(9)= 2.14$, $p > .05$. There was also no difference between the single-task auditory detection condition and the dual-task spatial processing task, $t(9)= 1.51$, $p > .05$.

Mean response times for tones were longer in the dual-task visual storage condition (599ms) than in the single-task auditory detection condition (284ms), $t(9)= 7.86$, $p < .001$. The same holds for the dual-task spatial processing condition (511ms), $t(9)= 10.55$, $p < .001$. The increase in time required to detect auditory tones when comparing single task conditions to dual task condition was significantly greater in the visual storage task (314ms) than the spatial processing task (227ms), $t(9)= 2.87$, $p < .05$.

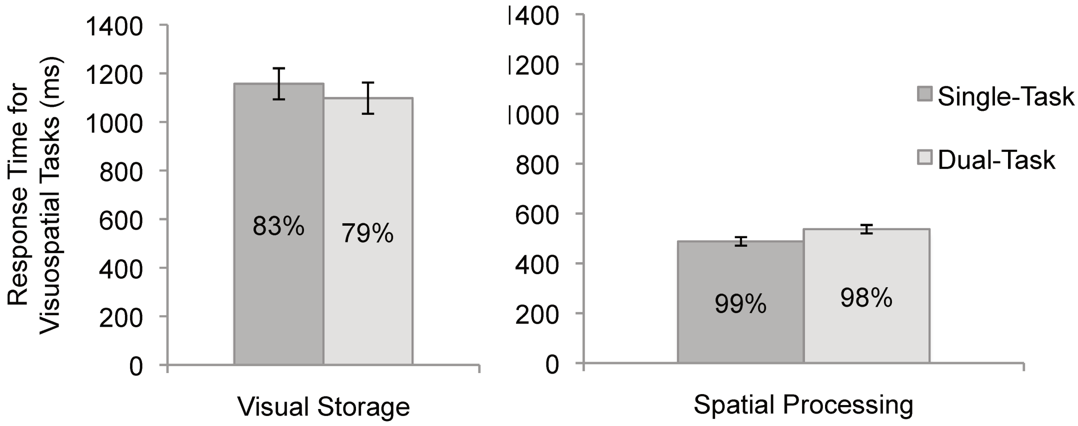

Figure 6: Mean response times (ms) for the visual storage and spatial processing tasks in the single-task (dark gray) and dual-task (light gray) conditions. Mean accuracy (% correct) is displayed at center of bars for the visual storage condition and mean response rate (%) is displayed at centre of bars for the spatial processing conditions. Error bars represent 95% confidence intervals according to Jarmasz and Hollands, 2009.

Visuospatial tasks

In the visual storage task, accuracy did not differ between single-task and dual-task conditions, $t(9)= 1.36$, $p > .05$. Similarly, response times did not differ between single-task (1157ms) and dual-task conditions (1098ms), $t(9)= .96$, $p> .05$. In the spatial processing task, accuracy did not differ between single-task and dual-task conditions, $t(9)= .931$, $p > .05$. However, response times were slower in the dual-task (537ms) than in the single-task (488ms) condition, $t(9)= 2.96$, $p < .05$.

Discussion

Participants did not miss more tones when performing the auditory detection task concurrently with either the visual storage or the spatial processing task as compared to baseline auditory detection task performance. Similar tone detection performance was taken as evidence that task demand in the visual storage and spatial processing tasks was comparable. Tone detection speed, however, did suffer more in the visual storage task than the spatial processing task. For this reason, the speed of the dot's motion in the spatial processing task was roughly doubled in Experiment 3.

EXPERIMENT 3

The purpose of Experiment 3 was to explore the influence of the secondary visual storage and spatial processing tasks on pursuit tracking now that these tasks were demonstrated as having comparable demands in Experiment 2. Performance on the pursuit tracking task was compared between dual-task conditions, where pursuit tracking was paired with either the visual storage or the spatial processing tasks, and compared to single-task performance when participants performed the pursuit tracking task in isolation. Performance on the secondary visual storage and spatial processing tasks was also compared between dual-task conditions and when these tasks were performed in isolation. It was hypothesized that the spatial processing secondary task would cause interference to pursuit tracking performance while the visual storage secondary task would leave pursuit tracking intact. Further, it was hypothesized that pursuit tracking would interfere with performance on the spatial processing task but not the visual storage task.

Method

Participants. Twenty-three undergraduate university students participated in the experiment for 1.5% bonus credit toward a psychology course. Participants had normal or corrected-to-normal vision. Three participants were removed from the analysis because their performance was at or below chance for one or more of the visuospatial tasks.

Design. A one-way within-subjects design was used with five conditions: single-task tracking, single-task visual storage, single-task spatial processing, dual task visual storage + tracking, and dual-task spatial processing + tracking. The tracking task replaced the auditory detection task in Experiment 3. Tracking performance was compared between single-task tracking and the two dual-task visuospatial conditions, and performance on the visuospatial tasks was compared between their single task and dual task conditions.

Materials. Identical to Experiment 2 with the addition of a participant-controlled cursor consisting of a red-hashed outline of the grid was displayed (See Figure 4) and the removal of the auditory stimulus. The cursor moved at a maximum of approximately 1360 px/sec on the x-axis and 650 px/sec on the y-axis to ensure that participants could catch up with the target moving at 300 px/s. Tracking performance was recorded as the Euclidian distance between the grid and the cursor, sampled at 10 Hz. Joystick sensitivity was set at a fine grain to ensure that the tracking task would be challenging - even for individuals with considerable experience using the controller.

Tasks. Visuospatial tasks were identical to those used in Experiment 2, except that the dot moved at a rate of 100 px/s in the processing task with a 500ms response window. For the tracking task, participants were instructed to use the controller’s right joystick to position the cursor such that it overlapped the target grid. Each trial started with both the target and the cursor aligned at the center of the screen. After a 500-ms delay the grid began moving along the pseudorandom figure-8 pattern and participants attempted to follow it with the cursor. The grid’s speed was increased exponentially from 0 to its maximum speed over the first 1000 ms of the trial to allow participants to accommodate to the change.

The dual-task conditions of the visual storage and spatial processing tasks were identical to those of Experiment 2 except that the cursor was presented along with the grid (see Figure 4).

Procedure. Participants completed an informed consent form and were given detailed instructions and a practice block before each of the five experimental blocks. Counterbalancing and experimental procedure were identical to Experiment 2 experiment except that the tone detection task was replaced with the tracking task in a single block that was always completed at the start of the experiment.

Results

Tracking Performance

The first lines of data from the start of each trial when the target and cursor speed were increasing from 0 to max were discarded from the analysis, resulting in a 4.25% data loss. A one-way repeated measures ANOVA was used to determine if participants' tracking performance was different between the single-task tracking, the dual-task visual storage, and the dual-task spatial processing blocks. Tracking performance, measured as root mean square error (RMSE) of Euclidean distance between the grid and cursor, was different between conditions, $F(2{,}38) = 26.67$, $p < .001$, $\eta_p^2 = .58$, $MSE \approx .001$. As shown in Figure 7, tracking performance was worse when combined with the spatial processing task than with the visual storage task, whereas tracking performance in the visual storage task did not differ from the single-task tracking condition.

Paired sample *t*-tests revealed that tracking error was greater for the dual-task spatial processing condition than for both the single-task tracking condition, $t(19) = 6.44$, $p < .001$, and the dual-task visual storage condition, $t(19) = 5.28$, $p < .001$. Tracking error did not differ between the single-task tracking and the dual-task visual storage conditions, $t(19) = 1.11$, $p > .05$.

Visuospatial task performance

Data trimming. Before the analysis, spoiled trials where no response was made were removed from the visual storage task conditions, 1.38% data loss. Because the dot moved very quickly during the spatial processing task, the response window was

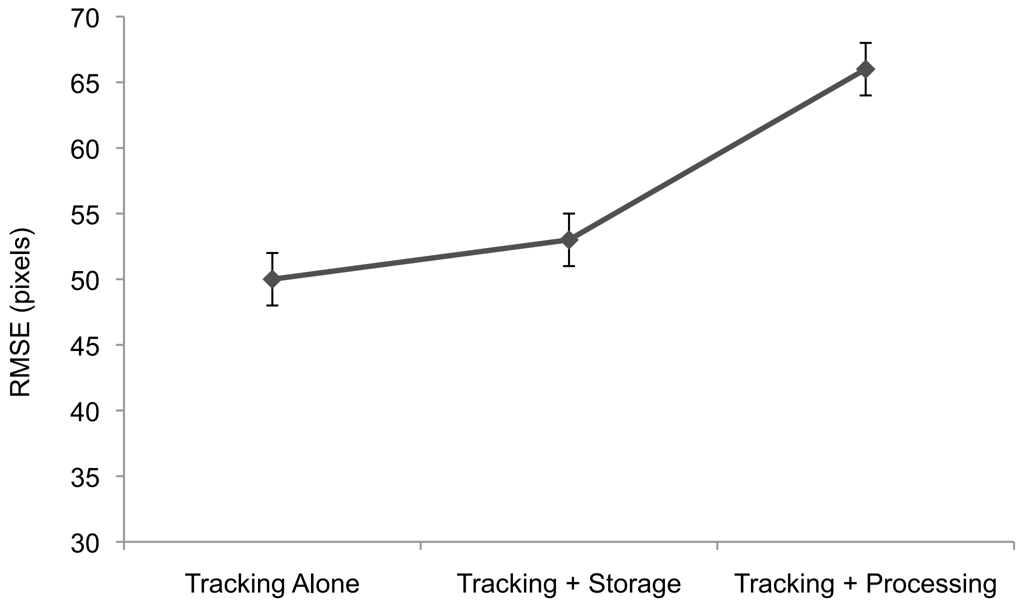

Figure 7. RMSE tracking performance (in pixels) between the target and the cursor as a function of Condition (single-task tracking, dual-task tracking + visual storage, and dual-task tracking + spatial processing), where error bars represent 95% confidence intervals according to Jarmasz and Hollands, 2009.

programmed to cap at 500 ms so as to not allow latent participant responses to overlap with new dot motion event windows. Capping the response window resulted in some erroneously coded response times, thus all response time under 200 ms were removed from the analysis, resulting in a loss of 5.51% of data for this task. The remaining RT data were trimmed according to Van Selst and Jolicoeur's (1994) procedure resulting in the loss of 0.25% of data.

Response rate. Because each trial of the visual storage task required only one response per trial, participants tended not to miss any responses and thus the response rate for this task was at ceiling. A response rate analysis of the spatial processing task, however, revealed significant difference as this task required participants to make quick responses at up to 10 times per trial. Indeed, participants missed more dot-motion changes during the dual-task spatial processing condition than during the single-task spatial processing condition , $t(19)= 7.23$, $p < .01$.

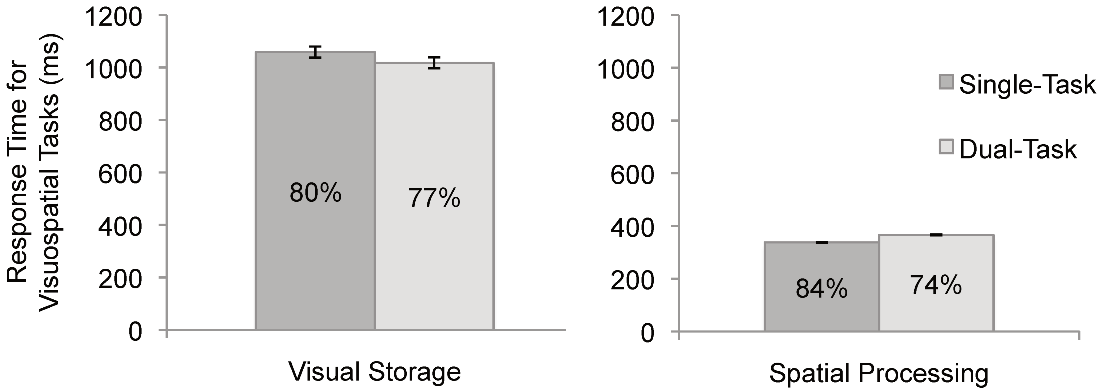

Figure 8: Mean response times (ms) for visuospatial tasks in single-task (dark gray) and dual-task (light gray) conditions in Experiment 3. Mean percent accuracy (% correct) is displayed above visual storage task conditions and mean response rate (%) is displayed above spatial processing task conditions. Error bars represent 95% confidence intervals according to Jarmasz and Hollands, 2009.

Because of the response window capping procedure, false alarms were not captured for analysis.

Accuracy. Mean percent accuracy scores were compared between single- task and dual-task condition for the visuospatial tasks. Unlike the response rate measure, accuracy was more meaningful for the visual storage than the spatial processing task. Percent accuracy did not differ between single-task and dual-task visual storage conditions, $t(19)= 1.23$, $p = .233$.

Response times. After removing incorrect responses, RTs were compared between single-task and dual-task condition of the visuospatial tasks (see Fig 8). In the visual storage task responses were not significantly different between the dual-task (1018 ms) and the single-task (1059 ms), $t(19)= 1.33$, $p > .05$. Conversely, mean RT was significantly faster in the single-task spatial processing condition (338 ms) than the dual-task spatial processing condition (366 ms), $t(19)= 9.44$, $p< .001$.

Discussion

Participants had considerable difficulty performing the pursuit tracking task concurrently with the spatial processing task, whereas the visual storage task did not interfere with participants' pursuit tracking ability. This pattern was repeated for the secondary tasks, where performance on the spatial processing task suffered when the task was done concurrently with pursuit tracking whereas performance on the visual storage task was not affected by pursuit tracking. This pattern of interference supports the hypothesis that a spatial processing task interferes with pursuit tracking (and vice versa) whereas a visual storage task does not affect interfere with pursuit tracking. This finding can be interpreted as evidence that visual storage and spatial processing are subserved by distinct components in visuospatial working memory.

An alternative account for the observed pattern of interference is that the secondary spatial processing (motion discrimination) task requires substantial motor output. To accurately perform this task, participants needed to generate differential up/down motor responses that may have been the locus of interference to pursuit tracking performance. This possibility is addressed in Experiment 4.

EXPERIMENT 4

The objective of Experiment 4 was to determine whether the interference in pursuit tracking by the secondary spatial processing task observed in Experiment 3 was due to motor output interference. To address this, the response paradigm for the secondary spatial processing task was simplified to a single button-press in Experiment 4.

Method

Participants. Twenty undergraduate university students participated in the experiment for 1.5% bonus credit toward a psychology course. Participants had normal or corrected-to-normal vision. Eight participants were removed from the analysis because their performance was at or below chance for one or more of the visuospatial tasks.

Materials. Identical to Experiment 3.

Tasks. Identical to Experiment 3, except that participants now pressed a single button to indicate when the dot changed direction instead of pressing the up or down button to indicate the dot's new direction.

Procedure. Identical to Experiment 3.

Results

Tracking performance

A repeated measures ANOVA was used to determine if participants' tracking performance was different between the single-task tracking, the dual-task visual storage, and the dual-task spatial processing blocks. The first lines of data from the start of each trial when the target and cursor speed were increasing from 0 to max were discarded from the analysis, resulting in a 2.24% data loss. Tracking performance, measured as root mean square error (RMSE) of Euclidean distance between the grid and the cursor, was indeed significantly different between blocks, $F(2,22) = 9.18$ $p< .01$, $\eta_p^2 = .46$, $MSE = 97.02$. As shown in Figure 9, tracking performance was worse when combined with the spatial

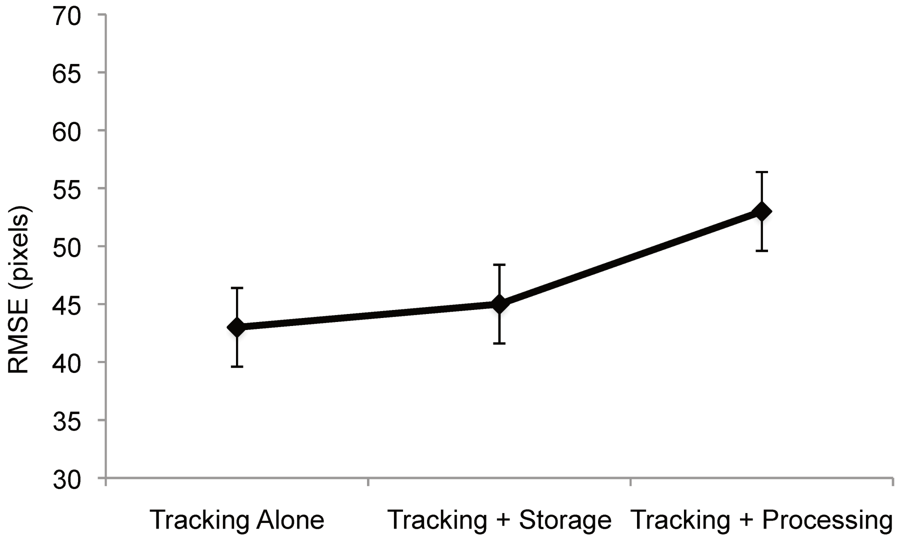

Figure 9. RMSE tracking performance (in pixels) between the target and the cursor as a function of Condition (single-task tracking, dual-task tracking + visual storage, and dual-task tracking + spatial processing), where error bars represent 95% confidence intervals according to Jarmasz and Hollands, 2009.

processing task than with the visual storage task, whereas tracking performance in the visual storage task did not differ from the single-task tracking condition.

Paired sample t-tests revealed that tracking error was greater for the dual-task spatial processing condition than for both the single-task tracking condition $t(11)=3.22$, $p< .01$, and the dual-task visual storage condition, $t(11)=4.23$, $p< .01$. Tracking error did not differ between the single-task tracking and the dual-task visual storage conditions, $t(11)= 1.15$, $p> .05$.

Visuospatial task performance

Data trimming. Spoiled trials where no response was made were removed from the visuospatial task data, 0.15% data loss. Once again all RTs under 200ms were removed to correct for RTs erroneously captured outside the 500ms response window, resulting in a loss of 6.16% of data. The remaining RT data were trimmed according to Van Selst and Jolicoeur’s (1994) procedure resulting in the loss of .32% of data.

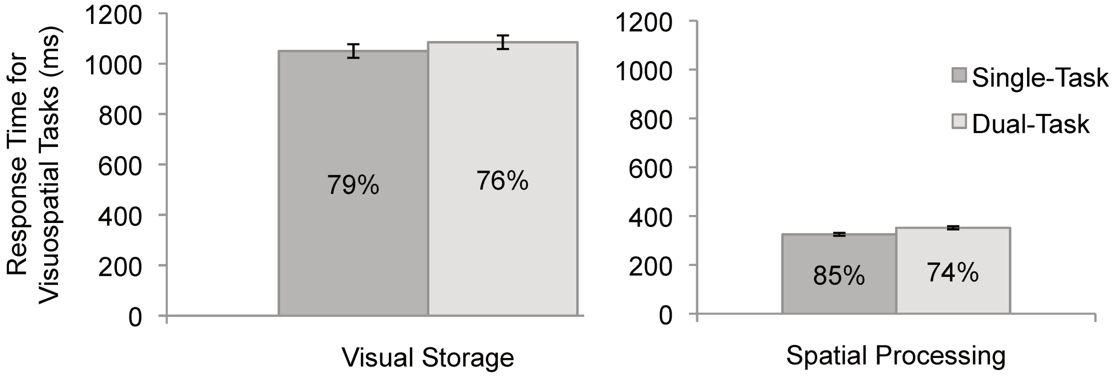

Figure 10: Mean response times (ms) to visuospatial tasks in single-task (dark gray) and dual-task (light gray) conditions in Experiment 3. Mean percent accuracy (% correct) is displayed above visual storage task conditions and mean response rate (%) is displayed above spatial processing task conditions. Error bars represent 95% confidence intervals according to Jarmasz and Hollands, 2009.

Response rate. Again the response rate for the visual storage task was at ceiling whereas the response rate in the spatial processing task declined from the single-task condition to the dual-task condition, $t(11)= 3.54$, $p< .01$.

Accuracy. In the visual storage task, mean percent accuracy was similar for the single-task and dual-task conditions, $t(11)= 1.31$, $p> .05$. There are no accuracy score associated with the spatial processing task since the response paradigm was reduced to 1 button for Experiment 4.

Response times. After removing incorrect responses, RTs were compared between single-task and dual-task condition of the visuospatial tasks (see Fig 10). In the visual storage task responses were not significantly different between the single-task (1050ms) and the dual-task (1085ms), $t(11)= 1.19$, $p> .05$. Conversely, mean RT was significantly faster in the single-task spatial processing condition (325ms) than the dual-task spatial processing condition (352ms), $t(11)= 4.37$, $p< .01$.

Discussion

The pattern of interference observed in Experiment 4 replicates that of Experiment 3. Participants had considerable difficulty performing the pursuit tracking task with the concurrent spatial processing task, whereas the visual storage task did not interfere with participants' pursuit tracking ability. Secondary task performance confirms the pattern, where participants' performance on the spatial processing task suffered when performed concurrently with pursuit tracking whereas performance on the visual storage task was not affected by pursuit tracking. These interference patterns support the hypothesis that a spatial processing task interferes with pursuit tracking (and vice versa) whereas a visual storage task does not interfere with pursuit tracking. The consistent findings between Experiments 3 and 4 are interpreted as evidence that visual storage and spatial processing are subserved by distinct components in visuospatial working memory.

GENERAL DISCUSSION

The purpose of the present research was to determine what types of secondary tasks would be most likely to interfere with the primary task of pursuit tracking in aviation. The current experiments departed from the standard experiments reported in the working memory literature in that they employed a dual-task approach in which the primary and secondary tasks were performed concurrently instead of the secondary task being performed during the primary task's retention interval. The current research was framed using Baddeley and colleagues' (1974; Logie, 1995) working memory model in which pursuit tracking is assumed to rely on spatial processing. With the assumption that each working memory system (and subsystem) is limited by a finite pool of cognitive resources, it was hypothesized that a motion detection task – which also relies on spatial processing – would interfere with pursuit tracking whereas a visual storage task (matching) would not. The data supported this hypothesis: the dot motion-detection task interfered with pursuit tracking (and vice versa) but the matrix-matching task did not. Importantly, this pattern emerged despite the dot-motion detection task and the matrix storage task demonstrating comparable task demand in the Experiment 2. Experiment 4 experiment addressed the concern that the pursuit tracking interference caused by the dot motion-detection task was at the motor response (output) level and was therefore not memory-based. Despite using a simplified motor response for the dot motion detection task, the same pattern of interference was observed: motion detection interfered with pursuit tracking whereas visual storage did not.

Implications for Working Memory Theory

The consistent pattern of data observed in Experiments 3 and 4 can be interpreted as support for distinct and separable components within working memory's visuospatial sketchpad: a visual cache for temporarily storing visual information and an inner scribe for processing spatial information. This interpretation is consistent with the literature describing distinct visual and spatial processes within visuospatial working memory being carried out by a visual cache and inner scribe, respectively (Logie, 1995). Interference patterns demonstrate a clear distinction between visual and spatial working memory tasks (e.g., Della Sala et al., 1999; Logie & Marchetti, 1991; Klauer & Zhao; 2004) and neurophysiological imaging demonstrates differences in brain activity when participant perform these different type of working memory tasks (Smith & Jonides, 1997). Research has shown that the locus of spatial processing interference occurs at a tasks' movement component or even at the anticipation of movement (e.g., Logie & Marchetti, 1991; Quinn & Ralston, 1986; Quinn, 1991). It follows that continuous monitoring, anticipation, and response to the movement in the dot motion task is responsible for the interference observed in the pursuit tracking task.

It is possible that the bi-directional interference between the pursuit tracking and dot-motion detection tasks arises due to task similarity (Pashler, 1994), where both tasks tap the same cognitive resources required to track and pursue moving objects. Indeed it is argued here that the dot-motion detection task is a low-level pursuit tracking task. It should be noted, however, that the dot-motion detection task is not simply a diluted up/down pursuit tracking task given that the visual frame in which the dot is moving up and down (i.e., the target grid), is also moving in 2-dimensional space. In order to detect directional changes, participants must compare the current motion to previous motion while suppressing motion information from the target grid. Thus the dot motion detection task requires the ability to detect changes to direction of motion of the dot but also the continuous updating of information about the motion of the target grid such that its contribution to the motion of the dot can be accounted for and parceled out. In this sense, the dual task spatial processing condition combines a pursuit tracking task with another layer of spatial processing: the processing of the spatiotemporal relationship between the target grid and the dot moving within it.

The bi-directional interference between the dot motion detection task and the pursuit tracking task observed in Experiment 3 could be ascribed to a conflict arising at the motor output level in that both tasks require similar motor responses to indicate directional change. If this pattern of interference were entirely due to motor-level effects, then one would expect it to disappear (or at least be less apparent) in Experiment 4 where participants only had to press a button to indicate a change in the dot's direction of motion. Given that the same pattern of interference was observed in Experiment 4, the interference between pursuit tracking and the dot-motion task cannot be attributed to a conflict arising at the level of the motor response.

Future Directions

Given the novelty of the (dot-motion) spatial processing task used here, it would be useful to determine if a more traditional spatial processing task (e.g., Shepard & Metzler's, 1971 rotation task) would yield the same results. Mental rotation tasks require visual stimuli to be manipulated in space with little, if any, reliance on stored visual information. As such, mental rotation can be thought of as a spatial processing by the inner scribe. A mental rotation task could be implemented in the current paradigm by having participants indicate whether a stimulus has been rotated or inverted. Given the limited space within the target grid and the desire to maintain the current paradigm's exclusion of a retention interval during the spatial processing task , the mental rotation stimuli would be a set of highly practiced alphanumeric characters (e.g., Cooper & Shepherd, 1973). Thus in lieu of a moving dot, the target grid would contain a letter or number that had been either rotated 180° or inverted (i.e., turned about its vertical axis). The finding that rotation/inversion discrimination also interfered with pursuit tracking would provide converging evidence that pursuit tracking is subserved by the visuospatial sketchpad's inner scribe and not by the visual cache.

A complementary dual-task study using a visual storage task as the primary task (instead of pursuit tracking) could bolster the claim that visuospatial working memory is comprised of two distinct subsystems: visual storage (cache) and spatial processing (inner scribe). If this complementary study showed that the primary storage task was affected by a secondary storage (matching) task, but not a secondary (dot-motion/rotation) task, then this would provide the same double dissociation pattern that delineated visual and spatial processes within visuospatial working memory (see Klauer & Zhao, 2004). Like the current experiments, the design of this complimentary visual storage study would be strongest if the primary visual storage task was continuous and allowed for the concurrent presentation of a secondary visual storage or spatial processing task. A continuous visual storage task is challenging to design given the constraints that the primary and secondary storage tasks must use stimuli that are sufficiently different so as not to introduce similarity based interference (Tulving, 1983) and must be simple enough to limit the demands placed on either spatial processing rehearsal or central executive resources. Another concern is that the primary visual storage task stimuli be stored for a retention interval long enough to introduce secondary tasks but not without transfer into long-term memory.

Implications for Aviation

The present findings confirm the hypothesis that a spatial processing task interferes with pursuit tracking (and vice versa), but a visual storage task does not. This pattern of data allows one to make inferences about which types of tasks will and will not interfere with flying an aircraft, insofar as many piloting tasks rely on the ability track targets (including one's own aircraft) in space. Some in-flight pursuit tracking tasks (e.g., flying in formation, air-to-air refueling) are so highly demanding that one would expect interference from any secondary task regardless of whether it is of a visual storage or spatial processing nature. There are, however, less demanding situations where interference from a only spatial processing task is expected.

Flying a corridor using a highway in the sky display is an instance where automation has relieved the pilot of many of the complexities of maintaining a flight heading, such as integrating verbal and visual information about the position and movement their own and other aircraft. The highway in the sky display has simplified the task of maintenance flight into simple pursuit tracking. Much like the manual inputs required to perform the pursuit tracking task reported in the present research, flying with a highway in the sky display requires that a pilot make manual adjustments to keep aligned within the visually presented boundaries of the corridor. Thus, if one accepts the assertion that flying with a highway in the sky display is a pursuit tracking task, then any other task that relies on spatial processing should interfere with flying. Further, flying a highway in the sky should interfere with any other spatial processing tasks a pilot is required to perform.

In highly automated flying situations, a number of tasks are of a supervisory nature. In this context, a secondary spatial processing task might be interpolating motion information from an instrument panel, such as that displayed on an attitude or heading indicator. Indeed, Masalonis, Duley, and Parasuraman (1999) found that participants took longer to detect failing instruments when engaged in a manual flight maintenance task than when monitoring an automated flight. Failure of automation for the navigation read out could be detected by visually glancing at the relative position of a needle (comparison of current and optimal needle position, a visual storage task) while failure of attitude alignment had to be inferred by a lack of relative motion (motion discrimination, a spatial processing task) between the representative horizon and aircraft symbology. To understand this instrument's display that participants needed to use spatial processing to determine the relative motion of two objects in the instrument. Thus when engaged in another spatial processing task, pursuit tracking, participants needed more time for the spatial processing task of reading the attitude indicator than when they were monitoring flight heading.

In sum, the present research has provided evidence for distinct and separable components within visuospatial working memory. Pursuit tracking was assumed to be a pure spatial processing task and was used to tap processing at the inner scribe of the visuospatial sketchpad. Pursuit tracking performance suffered when paired with another spatial processing task but not a visual storage task, suggesting visual storage and spatial processing tasks are carried out separately at a visual cache and inner scribe, respectively. This evidence suggests that pursuit tracking tasks in aviation will suffer when pilots are engaged in other tasks that require spatial processing but not those that require visual storage.

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Appendix A – SONA Posting

Study Name: Pursuit Tracking and Visuospatial Working Memory: A Dual Task Study

Experimenters' Names: James Howell, Masters Student, Institute of Cognitive Science; Robin Langerak, Masters Student, Human-Computer Interaction; & Jolie Bell, Ph.D. Student, Institute of Cognitive Science.

Experimenter's Phone: 613-520-2600 ext. 2487

Experiment Location: VSIM Building, room 2212

Description: How does visuospatial memory work? The purpose of this dual-task study is to determine if people use the same or different working memory sub-components to process and store visuospatial information. In this study, you will be asked to track a moving target while matching different types of visual patterns. This study has received clearance by the Carleton University Psychology Research Ethics Board (Ethics Approval: 12-101).

Eligibility Requirements: Normal or corrected-to-normal visual acuity

Duration: 1.5 hour

Percentage: 1.5 Percentage

Preparation: None

Appendix B – Informed Consent Form

Informed Consent Form

Study: **Pursuit Tracking and Visuospatial Working Memory: A Dual Task Study**
Faculty Sponsor: Dr. Chris Herdman, Department of Psychology, Carleton University, tel. 520-2600 x.8122

The purpose of this informed consent form is to ensure that you understand both the purpose of the study and the nature of your participation. The informed consent must provide you with enough information so that you have the opportunity to determine whether you wish to participate in the study. This study has received clearance by the Carleton University Psychology Research Ethics Board (Ethics Approval: 12-101). Please ask the researcher to clarify any concerns that you may have after reading this form.

Research Personnel: In addition to the Faculty Sponsor named above, the following people are involved in this research and may be contacted at any time should you require further information about this study.

Name	Title	Department	Email	Phone
Robin Langerak	Masters Student	Human-Computer Interaction	robin_langerak@carleton.ca	520-2600 x.2487

Other Contacts: Should you have any ethical concerns regarding this study, please contact Dr. Avi Parush. For any other concerns about this study, please contact Dr. Jo-Anne LeFevre.

Name	Position	Phone
Dr. Avi Parush	Chair, Psychology Research Ethics Board	520-2600 x.6026
Dr. Jo-Anne LeFevre	Director, Institute of Cognitive Science	520-2600 x.2693

Purpose: The purpose of this study is to investigate how visual information is represented in memory when displayed in combination with a tracking task.

Tasks: This study consists of 3 tasks: (1) pursuit tracking, (2) memory storage, and (3) memory processing. In the pursuit tracking task, you will be asked to track a moving target on a computer monitor using a mouse to align your cursor with the target. In the memory storage and processing tasks, you will be asked to indicate whether 2 briefly presented patterns of dots are the same (storage) or to indicate the directional changes of a moving dot (processing) by making a keypress response. The experimenter will explain these tasks in further detail to ensure you have understood the tasks.

Duration, Locale, and Compensation: Testing will take place in the VSIM Building, room 2212, and will last approximately 1.5 hour. You will receive 1.5% credits for your participation.

Potential Risks/Discomfort: There are no potential psychological risks associated with participation in this experiment. Please note that your performance on the task in this experiment does not provide an indication of your suitability for university studies. However, if you feel anxious and/or uncomfortable about your performance in this experiment, please bring your concerns to the researcher's attention immediately.

Anonymity/Confidentiality: All data collected in this experiment will be kept strictly confidential trough the assignment of a coded number and securely stored on a local computer for a maximum of ten years. Similarly, this Informed Consent form will be kept for a maximum of ten years before being destroyed. The information provided will be used for research purposes only. You will not be identified by name in any reports produced from this study. Further, the information is made available only to the researchers associated with this experiment.

Right to Withdraw/Omit: You have the right to withdraw from this experiment at any time without any penalty. Your participation in this experiment is completely voluntary.

I have read the above description of the study investigating how visuospatial information is processed and stored in working memory. By signing below, this indicates that I agree to participate in the study, and this in no way constitutes a waiver of my rights.

Name:__________________________________ Date:________________________________

Signature:________________________________ Witness:____________________________

Appendix C – Debriefing Form

Debriefing Form

Pursuit Tracking and Visuospatial Working Memory: A Dual Task Study

Thank you for your participation in this study. The purpose of this study was to determine how information is processed and stored in working memory's visuospatial sub-system. More specifically, we are interested in assessing whether doing two concurrent processing tasks (pursuit tracking and the processing task) will demand more cognitive resources than a processing task (pursuit tracking) combined with a storage task (the memory storage task). The findings from this investigation will help clarify whether visuospatial information is processed by two separate working memory sub-systems (one for processing and one for storage) or by a single sub-system. If you are interested in learning more about visuospatial working memory, then please see the following:

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This study has received clearance by the Carleton University Psychology Research Ethics Board (Ethics Approval: 12-101). Should you have any ethical concerns regarding this study, please contact Dr. Avi Parush (Chair, Psychology Research Ethics Board, 613-520-2600 ext. 6026). Should you have any other concerns about this study, please contact Dr. Jo-Anne LeFevre, (Director, Institute of Cognitive Science, 613-520-2600 ext. 2693) or any of the following individuals:

Name	Title	Department	Study Role	Contact Info.
Robin Langerak	Masters Student	Human-Computer Interaction	Principle Researcher	520-2600 x.2487
Dr. Chris Herdman	Professor	Psychology	Faculty Advisor	520-2600 x.8122