THE ROLE OF ATTENTIONAL CONTROL IN WORKING MEMORY: EFFECTS OF COGNITIVE LOAD, AGING AND STROKE

By

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To my wife, Adriana, and my three wonderful boys, Lucas, Tad, and Matthew.

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ABSTRACT

Working memory is a limited capacity system that relies on attentional control mechanisms to filter out task irrelevant information for optimal performance (Broadbent, 1958). The aim of this dissertation was to investigate the interactions between the closely related constructs of working memory and attentional control (e.g., Awh et al., 2006) in healthy and pathological aging (i.e., stroke). In both of these populations, deficits of attentional control (i.e., the ability to filter distractors) are thought to be a major contributor to declines in working memory performance. This dissertation examined distractor interference (DI) effects on the performance of healthy young adults, healthy older adults, and stroke survivors on an increasingly difficult working memory task. It was predicted that: a) regardless of group membership, the presence of distractors would result in increased response times (RT) and error rates (ER) compared to conditions in which there were no distractors, b) regardless of group membership, as task difficulty increased DI would increase (i.e., further increases to RTs and ERs when comparing distractor present and distractor absent conditions), and c) younger adults would show the smallest DI effects, older adults would show greater DI effects than younger adults and stroke survivors would show the largest DI effects compared to older and younger adults. The results suggest that, for relatively simple working memory tasks, attentional control mechanisms may not be engaged, as all participants showed significant DI effects. In contrast, in the more difficult working memory tasks, DI effects were smaller than in the simpler tasks. The current data suggests that there are optimal conditions under which attentional control mechanisms are available *and* are applied to minimize the impact of distractors. Moreover, age and stroke status did not appear to affect the ability to apply attentional control mechanisms. These results support the theory that some aspects of top-down attentional control may be preserved in healthy and pathological aging.

LIST OF ABBREVIATIONS USED

AIC – Akaike’s Information Criterion

ANOVA – Analysis of Variance

CDA – Contralateral Delay Activity

CI – Confidence Interval

DI – Distractor Interference

DLPFC – Dorsal Lateral Prefrontal Cortex

EEG – Electroencephalography

ER – Error Rate

ERP – Evoked Response Potential

fMRI – functional Magnetic Resonance Imaging

fNIRS – functional Near Infrared Spectroscopy

GLMM – General Linear Mixed Modeling

GAMM – Generalize Additive Mixed Modeling

LOE – Log-odds of Error

RT – Response Time

SAS – Supervisory Attention System

VCI – vascular cognitive impairment

WM – Working Memory

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CHAPTER 1 INTRODUCTION

1.1 OVERVIEW AND PURPOSE:

Working Memory is a limited capacity system crucial for higher order cognitive tasks, such as conversing, reading, or mental arithmetic. Given its limited capacity, optimal working memory functioning requires a gatekeeper, i.e., an attentional control mechanism to filter out irrelevant information so that only goal relevant information passes into working memory (Broadbent, 1958). Although working memory and attentional control are frequently studied independently of each other there is considerable overlap between these two constructs (Awh et al., 2006; Engle & Kane, 2003; Gazzaley & Nobre, 2012).

The aim of this dissertation was to examine the impact of distraction on working memory performance. The impetus for this research came from the observation that there is a burgeoning field of research targeting cognitive rehabilitation (for recent reviews see Cicerone et al., 2011; Melby-Lervåg & Hulme, 2013; Poulin, Korner-Bitensky, Dawson, & Bherer, 2012) which has, in large part, led to the emergence of commercial products designed to "enhance" or "rehabilitate" cognitive functioning (e.g., Lumosity and Cogmed). In this landscape of emerging techniques and technologies it is therefore imperative to determine which areas of cognitive functioning might be amenable to, or in fact in need of, enhancement or rehabilitative training as proffered by these kinds of products. In this dissertation the impact of concurrently presented visual distractors on working memory performance was assessed in samples of healthy young adults, healthy older adults, and stroke survivors in an effort to understand how aging and brain injury might adversely affect an individual's ability to "protect" the contents of working memory in order to maintain optimal task performance. The ultimate goal is to use the results of this work to inform the design of process and strategy based training programs for cognitive rehabilitation.

This dissertation is composed of two manuscripts resulting from four experiments that examined working memory performance in samples from the three aforementioned populations. This chapter provides a review of the most prominent working memory theories and our current understanding of how distraction influences working memory performance in healthy young adults. Subsequently, working memory and attention difficulties in aging and vascular disease, of which stroke is one presentation, will then be outlined and we will discuss the merits and disadvantages of the methodology we have selected to study working memory and attentional control. Finally, the chapter will conclude with a summary of the overall objectives of this dissertation and a brief introduction to the manuscripts presented in chapters two and three.

1.2 WORKING MEMORY AND SELECTIVE ATTENTION

1.2.1 WORKING MEMORY

Working memory, as outlined in one of the most prominent theories, is a capacity-limited system composed of two temporary memory stores – the phonological loop for verbal information and the visuospatial sketchpad for visuospatial information – and the central executive (Baddeley & Hitch, 1974; Baddeley, 1986). The phonological loop can be further broken down into a phonological store and the articulatory loop, where the phonological store holds information for a few seconds and the articulatory loop is a sub-vocal rehearsal process that allows for the maintenance of information held in the phonological store (Baddeley, 2003). A similar fractionation of the visuospatial sketchpad has also been proposed, wherein it is composed of a visual memory store and a rehearsal / retrieval mechanism dubbed the 'inner scribe' (Logie, 1995).

Latterly, Baddeley's working memory model was expanded to include a third temporary store, the episodic buffer (Baddeley, 2000). The episodic buffer can be thought of as the "workspace of the central executive" (described below) in which information from multiple modalities is bound together to form integrated episodes. According to Baddeley's model, this buffer is also the mechanism through which longer term memory representations are stored and retrieved.

Baddeley's conceptualization of the central executive (Baddeley, 2003) can be broadly thought of as a limited capacity attentional control system (similar to Shallice's Supervisory Attention System, SAS – Shallice, 1988) that serves several functions including: shifting attention between active sets of information (e.g., task switching), updating information held active in the slave systems (e.g., completing a mental arithmetic computation) and selective attention - preventing irrelevant information from intruding on the goal related task, either through inhibiting processing of task-irrelevant stimuli (Ahmed & de Fockert, 2012; Caparos & Linnell, 2010) or through conflict resolution between task-relevant and task-irrelevant stimuli in post-perceptual processing (Engle, Tuholski, Laughlin, & Conway, 1999; Nee et al., 2013; Pratt, Willoughby, & Swick, 2011).

Although Baddeley's theory of working memory is perhaps the most prominent, other useful theoretical frameworks such as Cowan's embedded process theory (Cowan, 1995) or Engle's working memory capacity model (Engle et al., 1999; Unsworth & Engle, 2007a) do exist. Cowan's hierarchical model proposes that working memory comprises long-term memory, activated memory (easily accessible but “outside” awareness), and the focus of attention (highest level of memory activation and “inside” awareness), and the central executive – which directs attention and voluntary processing). In Cowan’s account, memory is a unitary process rather than fractionated.

Research by Engle and colleagues has focused on variability in memory performance, examining why it is that some people are more successful at selectively attending to relevant information and retaining more information in memory, framing this as working memory capacity (Engle et al., 1999). The key of this model is that working memory capacity is the ability to hold information in mind *and* protect this information from being degraded by distraction.

Despite these differing theories, there is broad agreement that the role of working memory is as a set of processes designed for the temporary maintenance and manipulation of information held in mind in order to complete our normal activities of daily living (for an extended commentary on theoretical similarities and differences see Baddeley, 2012). Furthermore, in all accounts, attentional control mechanisms (i.e., selective attention processes) are needed to protect the contents of working memory from interference from task-irrelevant information. In a recent meta analysis (Nee et al., 2013), the authors reported that despite a multiplicity of research proposing differing functional organizations of the central executive, all of the frameworks agree on a common set executive functions: shifting attention between information sets, updating the content of active information sets, and preventing distractors from interfering.

1.2.2 WORKING MEMORY AND ATTENTIONAL CONTROL

Individual differences research, described above, supports strong links between working memory and attentional control (e.g., Engle et al., 1999; Unsworth & Engle, 2007b; Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005). Vogel and colleagues examined the event-related potentials of healthy young adults, generated while participants completed a visual working memory task. Participants were given a bilateral presentation of rectangles and were asked to only attend to either the left or right hemi-field of the display, as indicated by a central cue, and remember the orientation of the red rectangles. After a 900 ms delay participants then had to report whether the orientation of the currently presented red rectangles was a match to the previously presented targets. Individuals were presented with: 2 red rectangles, 4 red rectangles, or 2 red rectangles and 2 blue rectangles (in each hemi-field). Vogel et al. measured the contralateral delay activity (CDA) EEG waveform, a negative voltage that appears over the contralateral hemisphere to the to-be-remembered visual display, persists over the retention period, and is sensitive to the number of items being held in mind (Vogel & Machizawa, 2004), in each of the described conditions. Participants were split into high and low working memory capacity groups using a calculation to derive each participants working memory capacity (Cowan, 2001; Pashler H, 1988). In the subsequent analysis, Vogel et al. examined whether there was a relationship between working memory capacity and participants' attentional control ability (i.e., the ability to filter task irrelevant distractors), as measured by filtering efficiency. The authors proposed that if a participant is perfectly efficient at filtering the distractors, then the CDA for the 2 red targets / 2 blue distractors stimulus presentation would be the same as for the 2 red targets stimulus presentation. If a participant was perfectly inefficient at filtering the distractors then the CDA for the 2 red targets / 2 blue distractors stimulus presentations would be the same as for the 4 red targets stimulus presentations. Vogel et al results showed, that as predicted, the CDA for the 2 red targets / 2 blue distractors condition was similar to the 2 red targets condition for the high working memory capacity group and that the CDAs of the low working memory capacity group were more similar to the 4 red targets condition. The authors concluded that individuals with high working memory capacity are better able to protect the contents of working memory against distraction than are low working memory capacity individuals. Although these studies represent important work in defining the relationship between working memory and attentional control these types of studies have not examined the impact of distractors "making it into" working memory on working memory performance.

1.3 EFFECT OF DISTRACTORS ON WORKING MEMORY PERFORMANCE

To investigate how task-irrelevant information might interfere with working memory researchers have examined the impact of distractors when presented with the to-be-remembered target(s) at the encoding phase (Rutman, Clapp, Chadick, & Gazzaley, 2010) or when presented during the maintenance phase (Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005; Sreenivasan & Jha, 2007; Zanto & Gazzaley, 2009). Rutman et al. (2010) investigated how top down attentional control of visual processing might predict working memory performance using both behavioural (i.e., response times and accuracy) and electrophysiological (i.e., EEG) measures. Participants completed a delayed match to sample working memory task in which they had to remember either 2 faces or 2 scenes and determine whether a probe, presented 4 seconds after the encoding stage, was a match to either of the encoded stimuli. Stimuli were presented one at a time and could consist of: 2 faces, 2 scenes, or 2 images of overlapped faces and scenes. Thus, in some conditions participants had to remember the faces but ignore the overlapped scenes or remember the scenes and ignore the overlapped faces. Their results showed that participants took longer and made more errors when stimuli were overlapping. Rutman et al. also found a correlation between the neurophysiological measures (EEG, P1) and behavioural results such that better filtering, as measured by a Modulation index score taken in the first 100 ms of encoding (see Rutman et al., 2009 results section for a description of the measure), predicted greater working memory accuracy. Their results suggest that concurrent distractors do impair performance of a working memory task and that working memory performance is dependent on whether or not an individual can successfully filter out the distractors.

Working memory tasks both in the laboratory setting and in daily life vary considerably with respect to difficulty. Tasks can be made more difficult due to an increased number of items that need to be maintained (remembering a telephone number compared to remembering a credit card number) or by increasing the complexity of the mental operations that have to be performed (completing simple addition compared to finding the square root of a number). Although the work done by Rutman et al. (2010) supports the theory that concurrent distractors have a negative impact on working memory performance, positioning of the distractor relative to the target may also be a factor on the impact the distractor has. Rutman et al. employed a paradigm in which the distractor was superimposed upon the target, thus sharing the same physical space. As a result, participants are unable to use a spatial attentional control strategy, i.e., allocating attention to only a small portion of the visual field (sometimes referred to as the "attentional window"), which has been shown to reduce the impact of distractors in visual search tasks (Belopolsky & Theeuwes, 2010; Belopolsky, Zwaan, Theeuwes, & Kramer, 2007; Theeuwes & Van der Burg, 2007).

Some lines of research have examined changes in attentional control as a function of working memory load (e.g., de Fockert, Rees, Frith, & Lavie, 2001; Vogel et al., 2005). For example, in 2001, de Fockert et al. had participants perform a discrimination task in which they had to categorize printed names as either politicians or pop stars while ignoring distractor faces that were superimposed on the written names. These faces could be congruent with the printed name, incongruent with the printed name, or anonymous. Participants simultaneously completed a secondary working memory task in which they had to remember a sequence of five digits that were the same on every trial (low working memory load) or different on every trial (high working memory load). The behavioural results from their study indicated that distractor interference, defined as

$$\text{RT for incongruent condition} - \text{RT for congruent condition}$$

was greater in the high working memory load condition than in the low working memory load condition (de Fockert et al., 2001). The authors concluded increased working memory load results in less available executive resources to filter the visual distractors. However, it should be noted that the difference in distractor interference when comparing high working memory to low working memory conditions was small (32 ms) and the incongruent distractor faces did not affect error rates. These results suggest that even though the ability to filter distractors in early stages of processing may have been slowed, executive resources were still available to effectively resolve the target/distractor incongruence. It remains unclear whether increasing working memory load might further limit the availability of executive resources for attentional control.

1.4 WORKING MEMORY AND SELECTIVE ATTENTION IN AGING

Cognitive decline is common in otherwise healthy older adults and has implications for day-to-day living. Many older adults feel that this cognitive decline is one of the most difficult aspects of aging to cope with (Bayles, Kaszniak, & Tomoeda, 1987). These difficulties can affect multiple cognitive functions, but changes are most frequently reported in processing speed, attention and memory, as well as executive function (Craik & Salthouse, 2000).

Several models have been proposed to describe the mechanisms that underlie cognitive decline, including: 1) the processing speed hypothesis - performance decrements are attributed to a global reduction in the speed with which information is processed (Salthouse, 1996), 2) the executive deficit hypothesis - performance decrements are attributed to the more rapid erosion of executive control processes (West, 1996), and 3) the inhibitory deficit hypothesis (Hasher & Zacks, 1988). In their influential model of aging, Hasher and Zacks propose that age-related cognitive decline is a result of a failure to inhibit processing of task irrelevant information (Hasher & Zacks, 1988), i.e., failures of selective attention. Older adults are therefore likely to encounter difficulties in conditions such as those posed by the flanker task (Ericksen & Ericksen, 1974), in which they must resolve the conflict between the central target and the to-be-ignored flanking distractors (Weeks & Hasher, 2014). Indeed, data from numerous studies have supported Hasher and Zacks' inhibitory deficit hypothesis in working memory tasks in which the distractors are presented during the maintenance phase

(Gazzaley, Cooney, Rissman, & D’Esposito, 2005; Gazzaley & D’Esposito, 2007), in discrimination tasks where the distractors are presented at the same location as the targets during the encoding phase (de Fockert, Ramchurn, van Velzen, Bergström, & Bunce, 2009; Quigley & Müller, 2014; Zanto, Toy, & Gazzaley, 2010) and in the aforementioned flanker tasks, in which the distractors are presented simultaneously with the targets during the encoding phase, but spatially separated (Zhu, Zacks, & Slade, 2010). In all types of stimulus-distractor presentations older participants were disproportionately slowed and/or more error prone in the presence of distractors compared to younger adults. For example, Gazzaley et al. (2005) conducted an fMRI study in which they had younger and older participants complete a working memory task in which they were presented with a display that alternated between faces and scenes (2 faces and 2 scenes). On separate blocks of trials participants were instructed to: ignore scenes and remember faces, ignore faces and remember scenes, or passively view the display. After a 9 second delay participants made a forced-choice response indicating whether a probe item was present in the preceding series for memory blocks (i.e., remember faces or scenes) or to indicate the direction of a centrally presented arrow (i.e., passive viewing condition). Older adults were slower and made more errors than did younger adults. The fMRI data also suggested that the increased error rates and response times were a result of a reduced ability for older adults compared to young adults to suppress task irrelevant information, as measured by a ‘suppression index’ (‘passive viewing’ condition minus ‘ignoring scenes’ condition) and not as a result of reduced ability to attend to task relevant information, as measured by an ‘enhancement index’ (e.g., ‘attend scenes’ condition minus ‘passive viewing’ condition). Although the authors concluded that age related declines in working memory were a result of a reduced ability to protect the contents of working memory the authors also went on to examine inter-subject variability and found that "high-performing" older adults (i.e., top third) performed at similar levels to healthy younger adults and that this behavioural performance coincided with no significant difference in the suppression index of the two groups. Thus, although difficulties in suppressing task-irrelevant distractors may underlie poorer working memory performance in aging, there is considerable variability, and impaired distractor filtering in aging is not a forgone conclusion.

There appear to be some other conditions under which older adults are no more affected by distractors than younger adults such as in some visual search paradigms (Costello, Madden, Shepler, Mitroff, & Leber, 2010) and for conditions in which spatial selection (i.e., the previously described 'attentional window' is used to constrain visual attention to particular place in the visual field) of relevant stimuli can be employed (Quigley, Andersen, & Müller, 2012). For example, in the study conducted by Costello et al., (2010), healthy younger and older participants were presented with visual displays of varying sizes (4 to 12 items) comprising a target (circle) and task-irrelevant shapes (squares). Participants had to respond whether the target circle contained a plus symbol or an equal symbol. Trials were divided into *never* and *sometimes* conditions in which, half the time, one of the shapes was presented in a different colour than the rest of the shapes (i.e., a colour singleton). In the never condition, the colour singleton was never the 'target circle', and colour was therefore informative and the singleton could be ignored. In the sometimes condition, each shape was equally likely to be the colour singleton, rendering colour uninformative. Of relevance, when examining the raw RTs, Costello et al. found an Age × Distraction interaction showing that older adults were more affected (i.e., slowed) by the presence of a salient distractor (i.e., the colour singletons), measured as RT for trials with a colour singleton minus RT for trials without a colour singleton, than were younger adults. However, when the results were z-transformed to account for general slowing in aging, the Age × Distraction interaction disappeared. This led the authors to conclude that older adults can exhibit preserved attention control when compared to younger adults although the authors also suggested that this preservation may be reserved for non-verbal or simple verbal stimuli (such as single letters or numbers).

Nevertheless, the bulk of the evidence appears to point toward an age-related decline in the ability to inhibit the processing of task-irrelevant material, to the detriment of older adult performance on working memory / executive function tasks.

1.5 WORKING MEMORY AND SELECTIVE ATTENTION IN STROKE

In addition to general cognitive decline with healthy aging, older adults are also at increased risk for vascular cognitive impairment (VCI), a syndrome that ranges from mild cognitive difficulties in a single domain to Vascular Dementia (Gorelick et al., 2011; O'Brien, 2006). VCI may be brought about by subclinical vascular pathology, such as small-vessel disease, or stroke (Gorelick et al., 2011), and research suggests that age is the single largest risk factor for stroke (Sacco et al., 1997).

Individuals who have been affected by stroke commonly encounter attention and working memory difficulties (Cicerone et al., 2000, 2011). Reports on the incidence rate of post-stroke attention deficits are as high as 45-92% in the acute phase of recovery (Stapleton, Ashburn, & Stack, 2001) and although some of these deficits may resolve, attention difficulties are often chronic and significantly impact functional outcomes and activities of daily living. Post-stroke attention difficulties are evident on neuropsychological testing (e.g., (Hochstenbach et al., 2003; Hyndman, Pickering, & Ashburn, 2008; McDowd, Filion, Pohl, Richards, & Stiers, 2003; Robertson, Ridgeway, Greenfield, & Parr, 1997; Stapleton et al., 2001) and self-reported measures of daily function (McDowd et al., 2003). Although these attentional difficulties appear to be most severe during the acute phase, i.e., up to 2 months post stroke (Barker-collo et al., 2009), residual attention difficulties are also likely to be chronic (Barker-collo et al., 2009; McDowd et al., 2003; Robertson et al., 1997).

A few studies have examined the impact of stroke on attention control processes (e.g., Lavie & Robertson, 2001; Rinne et al., 2013; Snow & Mattingley, 2006). Lavie and Roberston (2001) examined how unilateral neglect, a post-stroke condition in which individuals have a bias for attending to the ipsilesional visual space compared to the contralesional visual space, affected the extent to which individuals could ignore a congruent or incongruent flanking distractor while completing a speeded 2-forced-choice response task (i.e., whether an ‘A’ or a ‘B’ was presented in the center of the display). The results showed that when an incongruent flanker was presented to the ipsilesional visual space, participants were significantly slower in responding on the central task than when the flanker was congruent. Conversely, when the flanker was presented to the contralesional space, no congruency effects were evident. Snow and Mattingley (2006) conducted a similar study in which unilateral neglect participants and healthy controls completed a speeded response task in which participants had to determine whether the centrally presented stimulus (a coloured letter) was the letter ‘A’ or ‘B’ (letter task), or whether the colour of the presented stimulus was red or green (colour task), while ignoring flankers that could be congruent or incongruent on one (i.e., colour or letter) or both dimensions (colour and letter). Flankers were presented on either the ipsilesional or contralesional side. Healthy controls showed flanker interference effects (i.e., slowed response times when an incongruent distractor was present) regardless of the position of the flanker, but only for the task relevant domain, i.e., if the task was letter identification only incongruent letter identities produced flanker interference effects. Conversely, neglect participants showed flanker interference effects for both task-relevant and task-irrelevant domains (i.e., both colour and letter) when flankers were presented to the ipsilesional side. In addition, neglect participants showed flanker interference effects when distractors were presented to the contralateral side, but only for the task relevant domain (i.e., colour or letter). These results suggest that information in the contralesional space may still be processed in neglect and that attention control processes may be adversely affected by stroke even in ipsilesional space, an aspect of attention control that was previously thought to be preserved.

The two studies discussed in the previous paragraph focused on a very specialized subset of the stroke population. However, as discussed above, it appears attention control difficulties may be present in the broader stroke population. Rinne and colleagues (2013) compared the performance of patients with an acute stroke to healthy controls on the ANT measuring the 3 separate attention networks: alerting, orienting, and executive function (filtering). Sub-analyses of the patient group (N = 102) revealed dissociable deficits in each of the 3 attention networks based on lesion location. The relevant finding for the current study is that, behaviourally, although stroke participants were slower and less accurate than healthy controls, there were no interactions between group membership and measures of alerting, orienting, or executive control, suggesting preservation of some aspects of attention control in stroke as a whole.

Overall, the data described here are equivocal with respect to the extent to which stroke, as a broad classification encompassing a variety of lesion locations, might affect attentional control. The data do support greater impairment of attentional control based on lesion location, e.g., right hemisphere stroke in the case of unilateral neglect (Rinne et al., 2013). However, it remains unclear how increased working memory demands (that require more attentional control) might further impact attentional control processes in stroke populations.

1.6 ASSESSING WORKING MEMORY ABILITY VIA THE N-BACK

One of the most commonly used measures for the assessment of working memory, particularly in neuroimaging studies, is the n-back task (Kane, Conway, Miura, & Colflesh, 2007; Kearney-Ramos et al., 2014; Owen, McMillan, Laird, & Bullmore, 2005). The n-back working memory paradigm is a task that requires on-line storage, monitoring, and updating of a continuously changing information set. The individual must monitor the identity or location of a series of stimuli and indicate whether the currently presented stimulus is the same as the stimulus presented 'n' trials prior to it (Owen, McMillan, Laird, & Bullmore, 2005). The 0-back task, in which participants must hold a single target in mind for the duration of the task and determine whether presented stimuli are a match or a mismatch to the target, is considered a 'control' task because it requires maintenance of the single target in memory and no updating, therefore requiring few central executive resources (Owen et al., 2005). In contrast, other values of *n*, such as the 1-back task, require increased central executive resources relative to the 0-back task, requiring both maintenance and updating of the stored item as the target changes on each trial. The central executive can be further taxed by increasing the value of n, thus increasing the number of items that have to be maintained *and* updated in working memory.

The preceding paragraph alludes to the way in which the n-back task might tap different resources in Baddeley's model of working memory. For instance, as noted above, the verbal 0-back task is considered a maintenance task. Based on Baddeley's model of working memory it would be predicted that the 0-back task would primarily recruit the phonological loop (i.e., the verbal memory store). In contrast, the 1-back task requires updating of the information held in working memory and the prediction would therefore be that in addition to the phonological loop, the central executive would be engaged in order to successfully update the phonological loop. As the level of n increases, this theory would further predict that additional central executive resources would be engaged to deal with the increasing workload. These predictions have been validated in neuroimaging studies using both fMRI and functional Near Infrared Spectroscopy (FNIRS; e.g., Callicott et al., 1999; Herff et al., 2013; Veltman, Rombouts, & Dolan, 2003). For example, Callicott et al (1999), used fMRI to examine changes in BOLD response within the Dorsal Lateral Prefrontal Cortex (DLPFC), an area of the brain commonly thought to be involved in working memory (Owen et al., 2005), with increasing levels of n in the n-back task (n = 1-3). The authors found that DLPFC activation exhibited an inverted-u activation pattern with increasing level of n. As the level of n increased to 2, DLPFC activation increased and error rates did not significantly increase. However for the 3-back task, DLPFC activation decreased, compared to 2-back levels, and this coincided with increased error rates on the 3-back compared to the 2-back. The authors concluded that central executive capacity was exceeded in the 3-back task and resulted in the decrease in performance. In a similar account, Herff et al. demonstrated the prefrontal cortex activation, as measured by fNIRS, correlated with the level of the n-back. As the level of n increased prefrontal cortex activation increased, lending further support to the theory that prefrontal cortical areas are crucial for working memory and that, with increased working memory load, there is increased recruitment of these areas (Herff et al., 2013). Although the results from both Callicot et al. and Herff et al. suggest that the n-back is activating areas required for working memory in a manner consistent with Baddeley's model, and that the level of activation is load dependent, their data cannot differentiate the extent to which different working memory resources (i.e., phonological loop vs. central executive) are differentially engaged for maintenance tasks compared to updating tasks.

In 2003, Veltman et al. (2003) examined the neurophysiological differences between maintenance and updating by using fMRI to compare brain activation for a commonly used updating task (i.e., the verbal n-back) to a commonly used maintenance task (i.e., Sternberg task). In the Sternberg task, participants are presented with a set of letters to remember. After a delay period they are then confronted with a probe, which could be a single or several letters, and asked to determine whether or not the probe(s) were a part of the to-be-remembered set. Thus, all the participants must do is maintain the information over the delay period. In their study, Veltman et al. use 3 levels of n (i.e., 1-back, 2-back, and 3-back) and set sizes of up to 7 for the Sternberg task. Their results showed that both tasks activated essentially the same network of resources, including DLPFC, but that the network was more ‘active’ for the n-back task than the Sternberg task. The authors also completed contrasts in which they compared the increase in activation of DLPFC when going from a 1-back to a 2-back updating task to the increase in DLPFC activation when going from a set size of 2 to a set size of 7 on the Sternberg maintenance task. They found that increasing load by 1 on the n-back task resulted in a greater increase of DLPFC activation than did increasing the Sternberg set size from 2 to 7. Thus the authors concluded that while maintenance and updating tasks may activate a largely similar network (including both frontal and posterior regions), increased DLPFC activation likely indicates additional activation of central executive resources. Overall, the preceding data suggest that the n-back maintenance and updating tasks recruit a largely similar network but that maintenance tasks likely recruit substantially less resources from the DLPFC than do updating tasks and that the n-back is able to target both maintenance resources (i.e., the phonological loop) and central executive resources (i.e., the central executive) found within Baddeley’s model of working memory.

The n-back task also appears to have good face validity as a measure of working memory. It requires the maintenance and updating of a dynamic stimulus set and might be seen as analogous to the processing required for such higher order functions as reading and conversing (i.e., it requires sequential organization of stimuli to generate meaning). The n-back has also been shown to demonstrate good convergent validity using a variety of study approaches (e.g., Schmiedek, Hildebrandt, Lövdén, Lindenberger, & Wilhelm, 2009; Shelton, Elliott, Hill, Calamia, & Gouvier, 2009; though see (Kane et al., 2007).

For example, a recent study examined the construct validity of the n-back task using a battery of standardized, neuropsychological tests to establish both convergent and discriminant validity of the n-back task (Kearney-Ramos et al., 2014). In a sample of 34 adults, Kearney-Ramos et al. found strong positive correlations between 2-back performance and neuropsychological tests thought to measure aspects of working memory including: Digit Span – Forward, Spatial Span – Forward, Spatial Span – Reverse, accuracy and timing of the Test of Everyday Attention (part 4; Elevator counting with reversal using visual stimuli), and Trail Making Tests (parts 2 – 4). They also demonstrated no correlation between the n-back and tests that are measures of processing speed and verbal fluency, which were not expected to correlate with n-back performance, including: Trail Making Test (parts 1 and 5), Boston Naming Test, the Halstead-Reitan Finger Tapping Test, and Test of Every Day Attention (part 2; Elevator counting). Although this study did suffer from a relatively small *n* (as with some of the previously mentioned studies) and would benefit from replication studies, the broad array of neuropsychological tests employed do provide further support that the n-back does correlate well with both experimental and clinical measures of working memory.

One weakness of this paradigm is that the control task (i.e., the 0-back) can only really serve as a control for the 1-back task when examining differences between simpler maintenance tasks and harder updating tasks that recruit central executive resources. Any differences between the control task and higher levels of n (e.g., 2, 3, or 4) are confounded by the difference in the number of to-be-remembered items in the higher level n-back tasks. The methodology in this dissertation also seeks to address this issue.

1.7 DISSERTATION OBJECTIVES

This dissertation seeks to examine the relationship between working memory and attentional control. Specifically, is the ability to attend to task-relevant stimuli, in the face of distractors, affected by the level of working memory load placed on the central executive, and how does this, in turn, affect performance on the central working memory task?

Within this larger framework this dissertation sought to answer 4 questions. First, how do visual distractors affect working memory performance for healthy younger adults? Second, to what extent does increased working memory load affect the ability of attentional control mechanisms to filter distractors and does this result in reduced performance on the working memory task? Does age change the effects of distraction on working memory performance in the context of increasing working memory load? Finally, does stroke further impact the effect of distraction on working memory performance as working memory load increases?

To answer these questions a variant of the n-back task was employed in which working memory load was conceptualized as having two dimensions: task (maintenance vs. updating) and targets (number of to-be-remembered items). Examination of distractor interference effects on working memory performance was conducted via an additional adaptation to the n-back paradigm such that it also had flanking distractors similar to Ericksen and Ericksen (1974). These distractors were inverted or rotated letters of the same size as the targets.

This experimental design allowed examination of three separate variables: distractors (present vs. absent), number of targets, and task (maintenance vs. updating).

Although the primary objective was to examine how distractors would affect working memory performance across varying working memory loads, to our knowledge, this is the first time that a series of n-back tasks have been devised that can separately assess the effect of “loading” the central executive (i.e., via changes in the task type) compared to “loading” the sensory stores (i.e., via an increase in the number of targets). By independently applying load to the central executive and the phonological loop we can directly test whether at least one slave system, the phonological loop, might in some way be involved in the working memory mechanisms underlying selective attention.

The following predictions were made regardless of the studied sample (i.e., younger, older, and stroke). We hypothesized increased response times and error rates as the number of targets increased and as the task changed from a maintenance task to an updating task. We also predicted a targets × task interaction such that response times and error rates would be minimally affected by the addition of a second target in the maintenance condition but would be significantly more affected by the addition of a second target in the updating condition.

Based on support from studies such as Rutman et al. (2009) and Gazzaley et al. (2005) that have found distractors do impact working memory performance, we predicted that response times and error rates would increase in the presence of distractors compared to distractor absent conditions (i.e., a distractor interference effect). Finally, we predicted a distractors × targets × task interaction such that distractors would have less impact on response times and error rates for maintenance tasks compared to updating tasks. Furthermore, distractor interference effects would stay the same even with the addition of a second target to the maintenance tasks but would get larger when a second target was added to the updating tasks. This last prediction stems from the hypothesis that during maintenance tasks the addition of a second target should place the additional working memory load on the phonological loop. As a result, central executive resources should still be available to protect the contents of working memory from task-irrelevant distractors. Conversely, in updating tasks the addition of a second target should require increased central executive resources for successful completion of the working memory task. Reduced availability of central executive resources for discrimination of task-relevant versus task irrelevant stimuli should therefore result in increased distractor interference effects, i.e., poorer performance in the face of distractors when central executive resources are consumed.

We hypothesized that age would affect the impact of distractors on working memory. Specifically, based on Hasher and Zacks' inhibitory deficit theory(Hasher & Zacks, 1988), we predicted that relative to healthy younger adults, healthy older adults would: a) be more affected by increases in task difficulty, resulting in greater increases in response time and error rates as the task became more difficult, b) be more affected by the presence of distractors in all conditions and c) that the presence of distractors would result in greater increases in response times and error rates for the older adults than for the younger adults.

Similarly, based on the theory that stroke produces increased distractibility and difficulties with attention and executive function (Barker-collo et al., 2009; McDowd et al., 2003; Robertson et al., 1997) we predicted that the working memory performance of stroke survivors would be more affected by task difficulty such that as the task became harder response times and error rates would increase at a greater rate than for the healthy older adults. In addition, we predicted that stroke survivors' working memory performance would be generally more affected by the presence of distractors and that as the task became more difficult the impact of distractors would increase (i.e., further increases in response times and error rates) at a disproportionately higher rate when compared to the healthy older adults.

1.8 OVERVIEW OF MANUSCRIPTS

This dissertation comprises two manuscripts, each aimed at answering specific questions in order to add to a greater understanding of how distraction impacts working memory performance.

1.8.1 DIFFERENTIAL EFFECTS OF DISTRACTORS ON WORKING MEMORY PERFORMANCE IN MAINTENANCE AND UPDATING TASKS

In this first manuscript we evaluated the impact of visual distractors on the working memory performance of healthy young adults. Two experiments were conducted in which separate participant groups completed varying levels of the n-back task in distractor absent and distractor present conditions. Generalized Linear Mixed Effects Models (GLMMs) were employed as an analysis technique to assess working memory performance via response times and error rates as a function of task difficulty and presence of distractors.

1.8.2 THE EFFECTS OF HEALTHY AND PATHOLOGICAL AGING ON TOP-DOWN CONTROL OF VERBAL WORKING MEMORY

In this second manuscript we evaluated the impact of visual distractors on the working memory performance of healthy older adults and stroke survivors. Again, two experiments were conducted, individually assessing distractor interference effects for each group, independently and then group performance differences were assessed using similar analytic methods to those described in the first manuscript.

CHAPTER 2 DIFFERENTIAL EFFECTS OF DISTRATORS ON WORKING MEMORY PERFORMANCE IN MAINTENANCE AND UPDATING TASKS

2.1 ABSTRACT

In the current study, our aim was to further investigate the interactions between the closely related constructs of working memory and selective attention (e.g., Awh et al., 2006).Working memory is a limited capacity system that relies on selective attention mechanisms to filter out task irrelevant information for optimal performance (Broadbent, 1958), but little research has been done to examine how distractor interference changes with increasing working memory load. Across two experiments, two groups of 20 healthy young adults completed an increasingly difficult n-back task in which participants also had to contend with flanking distractors on half of the blocks of trials. We predicted that participants would be slower and less accurate in distractor present conditions compared to distractor absent conditions. We also hypothesized that as the task became more difficult, additional recruitment of executive control resources for completion of the working memory task would result in reduced filtering ability and therefore increased distractor interference. Our results suggest that for relatively simple working memory maintenance tasks, top down filtering may not be applied. In contrast, in the more difficult working memory updating tasks there appear to be optimal conditions (i.e., 2-back) under which central executive resources are available *and* are applied to minimize the impact of distractors. However, once these central executive resources have been consumed by the working memory task (i.e., 3-back), central executive resources are no longer available for filtering and distractor interference increases in the predicted manner.

2.2 INTRODUCTION

Working Memory is a limited capacity system crucial for higher order cognitive tasks, such as conversing, reading, or mental arithmetic. Given its limited capacity, optimal working memory functioning requires a gatekeeper, a mechanism to filter out irrelevant information so that only goal relevant information passes into working memory – selective attention (Broadbent, 1958). The aim of the current study was to examine further the interaction between the closely related systems of selective attention and working memory (Awh, Vogel, & Oh, 2006; Engle & Kane, 2003).

2.2.1 WORKING MEMORY

Working memory, as outlined in one of the most prominent theories, is a capacity limited system composed of two temporary memory stores – the phonological loop for verbal information and the visuospatial sketchpad for visuospatial information – and the central executive (Baddeley & Hitch, 1974; Baddeley, 1986). The phonological loop can be further broken down into a phonological store and the articulatory loop, where the phonological store holds information for a few seconds and the articulatory loop is a sub-vocal rehearsal process that allows for the maintenance of information held in the phonological store (Baddeley, 2003). A similar fractionation of the visuospatial sketchpad has also been proposed, wherein it is composed of a visual memory store and a rehearsal / retrieval mechanism dubbed the ‘inner scribe’ (Logie, 1995).

Baddeley’s conceptualization of the central executive (Baddeley, 2003) can be broadly thought of as a limited capacity attentional control system (akin to Shallice’s Supervisory Attention System, SAS – Shallice, 1988) that serves several functions including: shifting attention between active sets of information (e.g., task switching), updating information held active in the slave systems (e.g., completing a mental arithmetic computation) and selective attention - preventing irrelevant information from intruding on the goal related task, either through inhibiting processing of task-irrelevant stimuli (Ahmed & de Fockert, 2012; Caparos & Linnell, 2010) or through conflict resolution between task-relevant and task-irrelevant stimuli in post-perceptual processing (Engle, Tuholski, Laughlin, & Conway, 1999; Nee et al., 2013; Pratt, Willoughby, & Swick, 2011).

Latterly, Baddeley's working memory model was expanded to include a third temporary store, the episodic buffer (Baddeley, 2000). The episodic buffer can be thought of as the "workspace of the central executive" in which information from multiple modalities is bound together to form integrated episodes. According to Baddeley's model, this buffer is also the mechanism through which longer term memory representations are stored and retrieved.

Although other theoretical frameworks have been proposed, such as Cowan's embedded process theory (Cowan, 1995) or Engle's working memory capacity model (Engle et al., 1999; Unsworth & Engle, 2007), there is broad agreement that the role of working memory is for the temporary maintenance and manipulation of information held in mind in order to complete our normal activities of daily living (for a commentary on theoretical similarities and differences see Baddeley, 2012). Furthermore, in all accounts, control mechanisms are needed to protect the contents of working memory from interference from task-irrelevant information.

2.2.2 EFFECT OF DISTRACTORS ON WORKING MEMORY PERFORMANCE

To investigate how task-irrelevant information might interfere with working memory, researchers have examined the impact of distractors presented concurrently with the to-be-remembered target(s) (Rutman et al., 2010) or when presented between target presentation and recall (Gazzaley, Cooney, McEvoy, et al., 2005; Sreenivasan & Jha, 2007; Zanto & Gazzaley, 2009). Rutman et al. (2010) investigated how top down control of visual processing might predict working memory performance using both behavioural (i.e., response times and accuracy) and electrophysiological (i.e., EEG) measures. Participants completed a delayed match to sample working memory task in which they had to remember either 2 faces or 2 scenes and determine whether a probe, presented 4 seconds after the encoding stage, was a match to either of the encoded stimuli. Stimuli were presented one at a time and could consist of: 2 faces, 2 scenes, or 2 images of overlapped faces and scenes. Thus, in some conditions participants had to remember the faces but ignore the overlapped scenes or remember the scenes and ignore the overlapped faces. Their results showed that participants took longer and made more errors when stimuli were overlapping. Rutman et al. also found a correlation between the neurophysiological measures (EEG, P100) and behavioural results such that increased selectivity, as measured by a Modulation index score taken in the first 100 ms of encoding (see Rutman et al., 2009 results section for a description of the measure), predicted greater working memory accuracy. Their results suggest that concurrent distractors do impair performance of a working memory task and that working memory performance is dependent on whether or not an individual can successfully filter out the distractors.

Working memory tasks both in the laboratory setting and in daily life vary considerably with respect to difficulty. Tasks can be made more difficult due to an increased number of items that need to be maintained (try remembering a telephone number compared to remembering a credit card number) or by increasing the complexity of the mental operations that have to be performed (completing simple addition compared to finding the square root of a number). Although the work done by Rutman et al. (2010) supports the theory that concurrent distractors have a negative impact on working memory performance, the overlapping stimulus presentation restricts the use of spatial selection processes, such as the attentional window proposed by Theeuwes et al. (e.g., Theeuwes & Van der Burg, 2007). Thus is seems the impact of distractors may depend, in part, upon which selection processes can be utilized. Other lines of research have focused on how increased working memory load or variability in working memory capacity might affect the extent to which task-irrelevant distractors are perceived and/or processed (de Fockert et al., 2001; Vogel et al., 2005), however, it is unclear whether the presence of distractors exerts the same influence on working memory task performance across varying degrees of task difficulty. It may be the case that, not only do the stimulus attributes determine which attentional control processes can be used, the amount of remaining working memory resources may be another determinant of which attentional control processes are used.

To investigate how distractor interference effects change as a function of working memory load we employed an n-back task in which we could independently manipulate the level of load placed on two subcomponents of working memory: the central executive and the phonological loop. The n-back working memory paradigm requires on-line storage, monitoring, and updating of remembered information (Owen, McMillan, Laird, & Bullmore, 2005). The individual must monitor the identity or location of a series of stimuli and indicate whether the currently presented stimulus is the same as the stimulus presented ‘n’ trials prior to it. The 0-back task is considered a ‘control’ task because it is essentially a discrimination task, needing only maintenance of the target in memory and no updating, therefore requiring few central executive resources (Owen et al., 2005). In contrast, other values of *n*, such as the 1-back task, require increased central executive resources relative to the 0-back task, requiring both maintenance and updating of the stored item as the target changes on each trial. The central executive can be further taxed by increasing the value of n, thus increasing the number of items that have to be maintained *and* updated in working memory.

One weakness of this commonly used paradigm is that the control task (i.e., the 0-back) can only serve as a control for the 1-back task when examining differences between simpler maintenance tasks and harder updating tasks that recruit central executive resources. Any differences between the control task and higher levels of n (e.g., 2, 3, or 4) are confounded by the difference in the number of to-be-remembered items in the higher level n-back tasks. To control for this confound, working memory load was manipulated across two dimensions: task (maintenance vs. updating) and targets (1 vs. 2). To examine distractor interference effects on working memory performance we adapted our n-back paradigm to have flanking distractors similar to Ericksen and Ericksen (1974). These distractors were inverted or rotated letters of the same size as the targets.

This experimental design allowed us to create three separate variables: distractors (present vs. absent), targets (1-target vs. 2-targets), and task (maintenance vs. updating).

Although our primary objective was to examine how distractors would affect working memory performance across varying working memory loads, to our knowledge, this is the first time that a series of n-back tasks have been devised to separately assess the effect of "loading" the central executive (i.e., via changes in the task type) compared to "loading" the slave systems responsible for maintenance of information (i.e., via an increase in the number of targets). By independently applying load to the central executive and the phonological loop we can directly test whether at least one slave system, the phonological loop, might in some way be involved in the working memory mechanisms underlying selective attention.

2.2.3 HYPOTHESES

We predicted main effects for the number of targets and the task such that response times and error rates would increase as the number of targets increased and as the task changed from a maintenance task to an updating task. We also predicted a targets × task interaction such that response times and error rates would be minimally affected by the addition of a second target in the maintenance condition but would be significantly more affected by the addition of a second target in the updating condition.

Based on support from studies such as Rutman et al. (2009) and Gazzaley et al. (2005) that have found distractors do impact working memory performance, we predicted a main effect of distractors such that response times and error rates would increase in the distractors present conditions compared to distractor absent conditions (i.e., a distractor interference effect). Finally, we predicted that a distractors × targets × task interaction (i.e., distractors would further interact with the number of targets × task interaction) such that distractor interference effects would stay the same even with the addition of a second target to the maintenance tasks but would get larger when a second target was added to the updating tasks. This last prediction stems from the hypothesis that during maintenance tasks the addition of a second target should place the additional working memory load on the phonological loop and not the central executive (i.e., all that is required is maintenance of an additional letter, there is no updating). As a result, central executive resources should still be available to protect the contents of working memory from task-irrelevant distractors. Conversely, in updating tasks the addition of a second target should require increased central executive resources for successful completion of the working memory task. Reduced availability of central executive resources for discrimination of task-relevant versus task irrelevant stimuli should therefore result in increased distractor interference effects, i.e., poorer performance in the face of distractors when central executive resources are consumed.

2.3 METHOD

2.3.1 PARTICIPANTS

Twenty participants (age 19-31; mean age = 23.3 years; 7 males) were recruited by word of mouth or through the Dalhousie University subject pool. Participants received either course credit or $10 per hour for completing the experiment. All participants were, by self-report, right-handed and free of neurological and/or mood disorders. This research was reviewed and approved by the Research Ethics Boards of the Capital District Health Authority. Informed consent was obtained in writing from all participants.

2.3.2 APPARATUS AND STIMULI

All tasks were completed on a 2.7 GHz iMac (Intel Core i5; 8 GB RAM; 27” monitor; AMD Radeon HD 6770; display resolution = 1900 × 1200, refresh rate = 120

Hz) running Mac OS X Lion (10.7.1). Programming of the experiment was completed using Python (2.5.2). Target letters (capital A through Z) and distractors (inverted or inverted and rotated letters – A through Z except: N, O, V, W, and Z) stimuli were generated in GIMP (http://www.gimp.org/) using 50 × 50 pixel transparent background and Arial font. The letters were therefore, approximately 1 × 1 degree of visual angle when participants were seated at a viewing distance of 60 cm. When present, contour-to-contour spacing of distractors was 1 degree of visual angle immediately above, below, to the left, and to the right of the central target (see Figure 2.1).

2.3.3 TASK

Participants completed an n-back task, in which they had to remember the stimulus identity (a letter) regardless of its location on the screen and to determine whether the presented letter was a target letter by responding “yes” or “no” via mouse button presses (left button = match, right button = mismatch). Participants completed the following 4 conditions both with and without concurrently presented distractors:

1-target maintenance: This condition is typically referred to as a 0-back task. Participants were asked to remember the *first item* in the stimulus set and indicate whether subsequent letters were a match or a mismatch to the first item. We operationalized this as a maintenance task, as successful completion of the task only requires maintaining the target item in memory for the duration of the task.

2-target maintenance: This condition is a modified version of the 0-back task. Participants were asked to remember the *first two items* in the stimulus set, and indicate whether subsequent letters were a match or a mismatch to either of the first two items. Similar to 1-target maintenance condition, we operationalized this as a maintenance task, as successful completion of the task requires maintaining 2 target items in memory for the duration of the task. This condition was added so that we might control for set size (i.e., number of targets) when evaluating the effect of task on performance (i.e., updating and maintenance).

1-target updating: This condition is typically referred to as a 1-back task. Participants were asked to determine whether the stimulus on the screen was a match or mismatch to the item seen on the previous trial. In this condition participants not only need to keep the target item in mind, but they also must constantly update the target item identity on each trial and we have operationalized this as an updating task.

2-target updating: This condition is typically referred to as a 2-back task. Participants were asked to determine whether the stimulus on the screen was a match or mismatch to the item seen two trials ago. In this condition participants not only need to keep the 2 target items in mind, but they also must constantly update the target item identities on each trial. This has also been operationalized as an updating task.

All participants completed the tasks in the following order: 1-target maintenance (distractors absent), 1-target maintenance (distractors present), 2-target maintenance (distractors absent), 2-target maintenance (distractors present), 1-target updating (distractors absent), 1-target updating (distractors present), 2-target updating (distractors absent), and 2-target updating (distractors present). See Figure 2.1 for an example of a typical trial. Stimuli were presented for 500 ms with a 2500 ms inter-stimulus interval. Each participant completed a total of 24 blocks of trials. In half of the blocks of trials participants were instructed to ignore distractor stimuli, which were 4 inverted or mirror-reversed letters (all the same) presented concurrently with the target stimulus placed symmetrically at a distance of 1 degree of visual angle from the target).

2.3.4 PROCEDURE

All participants were tested individually in one 75-minute session. Participants were seated in front of the stimulus computer at a distance of approximately 60 inches so that stimulus size was consistent across participants. Participants were instructed to complete the tasks as quickly and as accurately as possible (i.e., no bias towards speed or accuracy) and, when present, to ignore distractors because they were irrelevant to the task. Participants completed one block of practice trials for each task, and were provided with auditory accuracy feedback (bell = correct, buzzer = incorrect). They then completed two test blocks for each condition, with no feedback on any task condition. Each block of trials consisted of 20 match and 20 control trials. Twelve additional "foil"[1] trials were added to the 2-target updating task in an effort to maximize the use of a recollection strategy rather than a familiarity based strategy (52 trials for 2-back).

2.3.5 STATISTICAL ANALYSIS

Analysis of response time (RT) and error rate (ER) data was conducted using generalized linear mixed models (GLMMs; Pinheiro & Bates, 2000). Lawrence and Klein (2012) provide a detailed rationale and concise explanation of the statistical procedures involved when using GLMMs, and provide an example and rationale specifically for the use of GLMMs for analysis of RT and ER. Their work also highlighted that the results obtained using GLMMs are quite similar to those found when using ANOVA but with

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[1] A trial is considered a foil when the currently presented stimulus is a match for n-1 but not n-2.

several additional benefits, including: fewer assumptions about the data and the underlying distribution, superior handling of missing data, improved statistical power through assignment of random effects (i.e., it is possible to explicitly model uninteresting effects such as inter-subject variability), and specifying the distribution family of the variable of interest (e.g., error data can be treated as a binomial distribution).

In the current experiments GLMMs were used to analyze three effects of interest to test the above hypotheses: distractors (yes vs. no), targets (1 vs. 2 targets), and task (maintenance vs. updating) on RT and ER. Models were compared via a likelihood ratio (i.e., the ratio of the probabilities of the data comparing each of the two models), and Akaike's information criterion (AIC, Akaike, 1974) was applied. The final AIC-corrected likelihood ratios are presented here as "bits of evidence" using the log-base-2 scale. The sign of the likelihood ratio indicates whether the data provide support for the effect in question (+) or its respective null (-), and the absolute magnitude of the likelihood ratio indicates the strength of evidence for the supported hypothesis. Royall (1997) proposed that a likelihood ratio of 8 reflects plausible evidence in favour of one hypothesis over another. In the current studies, a likelihood ratio of 8 is equal to 3 "bits of evidence" (i.e., 8 in the log-base-2 scale = 3), and was used as a cut-off point (as in Clouter et al., accepted; Lawrence & Klein, 2012), representing a significant finding.

As in Lawrence and Klein (2012), visualizations of data were obtained by a posteriori bootstrapping point estimates (i.e., cell means) and confidence intervals (estimation of intra-subject variability) from the models. Analysis was coded in R (Version 3.0.0; R Development Core Team, 2013) using the functions in the ez package (https://github.com/mike-lawrence/ez) for analysis and the ggplot2 package (Wickham, 2009, 2012) for visualizations.

2.4 RESULTS

Figure 2.2 provides a visualization of the point estimates and 95% Confidence Intervals of both correct RT and ER for all conditions. All trials with RTs less than 200 ms were excluded from the analysis (<%1 of trials).

As can be seen in Table 2.1, the data support the 3-way interaction of distractors × targets × task for RT (in ms) and a main effect of targets on ER (in log-odds). All other main effects or lower order interactions were either unsupported, or were captured by the higher order interaction noted above. See Table A1 in Appendix A for a comparison of the currently used Mixed Effects Analysis and typical ANOVA.

2.4.1 EFFECT OF TARGETS AND TASK ON WORKING MEMORY PERFORMANCE

Although response times were characterized best by the 3-way interaction described below, we also examined the lower order targets × task interaction as a check to ensure our manipulations were successful in creating successively more difficult tasks. As predicted, response times increased as the task became more difficult such that participants' response times were shortest for the 1-target maintenance condition, RT = 540 ms, 95% CI [478, 598], longer for the 2-target maintenance condition, RT = 595 ms, 95% CI [533, 653], longer still for the 1-target updating condition, RT = 627 ms, 95% CI [566, 686] and longest for the 2-target updating condition, RT = 837 ms, 95% CI [777, 895]. Finally, the addition of a second target had a much greater impact on response times in the updating condition RT_{diff} = 209 ms, 95% CI [197, 221] than it did in the maintenance condition, RT_{diff} = 55 ms, 95% CI [43, 67].

A main effect of targets was found for error rates, such that participants made more errors when there were two targets, ER = -3.0[2] log-odds of error base-2 (LOE), 95% CI [-3.1, -2.8] compared to when there was one target, ER = 3.3 LOE, 95% CI [-3.5, -3.1]. However task was not found to affect error rates nor did we find evidence for the predicted targets × task interaction. Thus although our manipulations of targets and task were successful, changes in performance were reflected primarily in the response time domain.

2.4.2 EFFECT OF DISTRACTORS ON WORKING MEMORY PERFORMANCE

To aid in the interpretation of the 3-way interaction of distractors × targets × task difference scores were used to create a measure of Distractor Interference (DI) for each of the 4 tasks as follows (see Figure 2.3):

$$□□ = \text{condition (distractors present)} - \text{ same condition (distractors absent)}$$

As predicted, the presence of distractors resulted in longer response times than when distractors were absent for all conditions. However, contrary to our hypotheses, the DI was higher for the 2-target maintenance task than for the 1-target maintenance task $\mathrm{DI}_{\mathrm{diff}}$ = 34 ms, 95% CI [10, 59], and was the largest observed DI compared to all other conditions (i.e., maintenance and updating). Also contrary to our prediction of increased distractor interference with increased task difficulty, the DI was *smaller* for the 2-target updating task than for the 1-target updating task, $\mathrm{DI}_{\mathrm{diff}}$ = -48 ms, 95% CI [-72, -25] and

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[2] Mixed effect modeling allows analysis of error data as a binomial event (optimal) rather than viewing it as proportional (i.e., percentage correct). The “log-odds of error” scale, in which this modeling was conducted has the following corresponding values to the proportional scale: a value of 0 represents an error rate of 50%, –1 represents an error rate of about 27%, –2 represents an error rate of about 12%, and –3 represents an error rate of about 5%.

was the smallest observed DI when compared to all other conditions. The presence of distractors did not influence error rates.

It is possible that the small DI observed during the most difficult, 2-target updating, task could have been a result of the relatively longer overall RTs for that condition. To investigate this possibility further, the DI was examined across the entire RT distribution by computing RT quantile values for each effect and interaction term. Quantile values were added to the GLMMs as a fixed effect and treated with generalized additive models (GAMMs; Hastie & Tibshirani, 1990; Wood, 2006), which allows nonlinearity in the predictions and therefore allowed quantiles to interact in a nonlinear way with other fixed effects (i.e., targets and task). The result is a plot that allowed us to examine the DI across quantiles of the RT distribution (Figure 2.4). Visual inspection of Figure 2.4 suggests that the DI steadily increased across the RT distribution for both maintenance conditions. In contrast, the DI stayed the same across the RT distribution for the 1-target updating task but the DI for the 2-target updating task got smaller as RTs increased and eventually vanished at the longest RTs. The negative slope of the DI for the 2-target updating task does suggest that the reduced DI for the 2-target updating task may in part be a result of longer response times. However, as is also apparent in Figure 2.4, the DI was smaller for the 2-target updating task than for the any of the other conditions at across the majority of the quantile distribution, suggesting that there may be other processes at play (see Figure A1 for an alternative delta plot further demonstrating differential DI effects at similar RTs).

2.5 DISCUSSION

Experiment 1 examined how the presence of visual distractors might affect performance on a working memory task as task demands increased. Although our findings were predominantly in the response time domain, in general, manipulations of targets (1 vs. 2) and task (maintenance vs. updating) produced the expected reductions in performance (i.e., longer response times or increased error rates). Consistent with our hypothesis that the presence of distractors would impact working memory performance, DI effects were present for all conditions. However, contrary to our hypotheses, the DI effect, i.e., the amount of extra time that was required on trials containing distractors compared to those that did not have distractors, was not consistent across number of targets in the maintenance conditions, and instead increased when the number of targets increased. This suggests that either the phonological loop is involved in selective attention or that additional central executive resources were recruited for maintenance of a second item and resulted in less central executive resources available for selective attention.

We hypothesized that the DI would be larger for updating conditions than for maintenance conditions because additional central executive resources would be recruited for the working memory task, thereby reducing the central executive resources available for selectively attending to task-relevant targets while also ignoring task-irrelevant distractors. However, our results indicated the DI was *smallest* compared to all other conditions for the 2-target updating condition, equivalent between the 1-target updating and 1-target maintenance conditions, and *largest* compared to all other tasks for the 2-target maintenance task.

We propose that as task difficulty increased, participants may have applied more stringent attentional control to minimize the effects of the irrelevant distractors in order to better attend to the relevant material. That is, during the maintenance task, although central executive resources were available, they were not deployed because of the simplicity of the task. Even though DI increased when participants had to maintain two items in memory compared to just one item, the task was still performed quickly and with few errors. Given the continued ease of the task, additional top-down control mechanisms may not have been brought online, resulting in increased DI. However, reduced DI effects during the 2-target updating task also suggest that there were remaining central executive resources for discrimination of task relevant from task irrelevant stimuli, even with increased task difficulty, and that there are some conditions under which the effects of concurrent distractors can be suppressed.

2.6 EXPERIMENT 2

Although participants in Experiment 1 were instructed to ignore the task irrelevant distractors, performance in all conditions was slowed by the presence of distractors. That performance was slowed most by distractors in the 2-target maintenance task and slowed least by distractors in the 2-target updating task led us to the suggestion that: a) central executive resources may still have been available for top-down selection of task relevant stimuli and suppression of task irrelevant stimuli in all conditions and that b) top-down control strategies were brought online when the task became sufficiently difficult.

We interpret Experiment 1 data to suggest that despite the instructions, participants did not feel it was necessary to “effortfully” ignore irrelevant distractors until the task became more difficult. Thus, distractors may be negatively impacting performance, but to an extent that participants consider phenomenologically inconsequential. In Experiment 2 we sought to: a) replicate the Experiment 1 finding that sufficient task difficulty is required before selective attention is enacted by the individual, and b) determine whether this selectivity could be maintained in the face of even greater working memory demand, via increasing the number of targets in both maintenance and updating conditions.

2.6.1 HYPOTHESES

Experiment 1 results suggest that distractors primarily affect response time but not error rates, thus our hypotheses for Experiment 2 place a greater emphasis on the response time domain than error rates. Based on the supposition that the maintenance task in Experiment 1 was not a sufficiently difficult task to induce participants to employ selective attention processes we predicted that distractor interference (DI) in Experiment 2 would increase as the number of targets increased. This supposes that even with more items to maintain, participants would still find maintenance tasks to be easy and participants would be less inclined towards "effortful" selection against distractors. Based on the supposition that central executive resources were available *and* employed for selectively attending to task-relevant information when the task was sufficiently difficult, we predicted that DI would be smaller during updating conditions with an n or 2 or higher. Once central executive resources are completely consumed by the central task, we would predict that the DI would begin to increase again with increasing values of n, however we made no predictions regarding what level of n would produce an inflection point towards increased DI.

2.7 METHOD

2.7.1 PARTICIPANTS

Twenty healthy young (age 18-27; mean age = 21.55 years; 13 males) participants were recruited by word of mouth or through the Dalhousie University subject pool. Participants received either course credit or $10 per hour for completing the experiment. All participants were, by self-report, right-handed and free of neurological and/or mood disorders. This research was reviewed and approved by the Research Ethics Boards of the Capital District Health Authority. Informed consent was obtained in writing from all participants.

2.7.2 APPARATUS AND STIMULI

Apparatus and stimuli and procedure were identical to those used in Experiment 1.

2.7.3 TASK

The Experiment 2 task was identical to the Experiment 1 task except that the number of targets could be 1, 2, 3 or 4 instead of just 1 or 2, as in Experiment 1. This resulted in 16 total conditions: 4 maintenance conditions without distractors, 4 maintenance conditions with distractors, 4 updating conditions without distractors, and 4 updating conditions with distractors.

2.7.4 PROCEDURE

All participants were tested individually in one 80-minute session. Participants were seated in front of the stimulus computer at a distance of approximately 60 inches so that stimulus size was consistent across participants. Participants completed one block of

10 practice trials for each task, and were provided with auditory accuracy feedback (bell = correct, buzzer = incorrect). They then completed two test blocks of 36 trials for each condition, without feedback. As in Experiment 1, participants completed all of the maintenance tasks first from lowest level of n to highest and then the updating tasks, from lowest level of n to highest. For each level of n, order of distractor present blocks was randomized for each participant to control for order effects on the distractor interference.

2.8 RESULTS

Figure 2.5 provides a visualization of the point estimates and 95% Confidence Intervals of both correct RT and ER for all conditions. Due to a technical error during data collection, the 1-target conditions were not analyzable and are not included here. As can be seen in Table 2.2, there was evidence of a 3-way interaction, distractors × targets × task type, for both RT and ER.

2.8.1 EFFECT OF TARGETS AND TASK ON WORKING MEMORY PERFORMANCE

As in Experiment 1, although the data are best described by the 3-way interaction, we first examined the targets × task interaction to ensure the addition of more targets to the maintenance and updating conditions resulted in the desired increases in task difficulty.

2.8.1.1 Maintenance Conditions

As predicted, response times were fastest for the 2-target maintenance condition, RT = 629.13 ms, 95% CI [567, 692], significantly longer for the 3-target task RT = 677 ms, 95% CI [616, 740] compared to the 2-target maintenance condition, and significantly longer again for the 4-target task RT = 730 ms, 95% CI [721, 847] when compared to the 3-target condition. Error rates showed a similar trend as participants were most accurate in the 2-target task, ER = -3.2 LOE, 95% CI [-3.4, -2.9] but showed non-significant differences in error rates when comparing the 2-target and 3-target maintenance conditions and when comparing the 3-target and 4-target maintenance conditions. However, participants were more likely to make errors in the 4-target maintenance condition, ER = -2.9 LOE, 95% CI [-3.1, -2.7] than in the 2-target maintenance condition.

2.8.1.2 Updating Conditions

Similar to the maintenance condition, response times were fastest to the 2-target updating condition, RT = 786 ms, 95% CI [721, 847] and significantly slowed by the addition of a third target in the 3-target updating condition, RT = 852 ms, 95% CI [790, 916]. However, unlike in the maintenance condition, response times were significantly *faster* for the 4-target updating condition, RT = 812 ms, 95% CI [750, 869] than for the 3-target updating condition, though still longer than the 2-target updating condition. Increasing the number of targets also resulted in increased error rates such that participants were most accurate in the 2-target updating condition, ER = -2.5 LOE, 95% CI [-2.7, -2.3], made significantly more errors in the 3-target updating condition, ER = -1.8 LOE, 95% CI [-2.0, -1.6] compared to the 2-target updating condition and more errors again in the 4-target updating condition, ER = -1.5 LOE, 95% CI [-1.7, -1.3], compared to the 3-target updating condition.

Also of note is that response times and error rates were greater in the 2-target updating task compared to the 4-target maintenance task, indicating that participants found even the ‘simplest’ updating condition was more difficult than the ‘hardest’ maintenance condition.

2.8.2 EFFECT OF DISTRACTORS ON WORKING MEMORY PERFORMANCE

As in Experiment 1, to aid in the interpretation of the distractors × targets × task interaction observed in Experiment 2, the DI for each condition has been calculated and is visualized in Figure 2.6.

2.8.2.1 Maintenance Tasks

The top left panel of Figure 2.6 shows that Distractor Interference (DI) was significant regardless of the number of targets and analysis indicated there were no DI differences between conditions. As can be seen in the bottom left panel of Figure 2.6, participants were *less* likely to make an error in the presence of distractors for the 2-target condition, DI = -0.5 LOE, 95% CI [-0.9, -0.1]. This represents a significantly different DI than was observed in the 3-target condition, DI_{diff} = -0.6 LOE, 95% CI [-1.1, -0.1] and the 4-target condition, DI_{diff} = 0.8 LOE, 95% CI [-1.3, -0.3]. In both of the latter conditions, the presence of distractors did not impact ER, nor did they differ significantly from each other.

2.8.2.2 Updating Tasks

As can be seen in the top right panel of Figure 2.6, DI was significant when participants had to remember and update two or three targets but not when they had to remember and update 4 targets. The DI was significantly larger for the 3-target condition than it was for the 2-target condition, DI_{diff} = 55 ms, 95% CI [8, 100]. The bottom right panel of Figure 2.6 shows that participants were more likely to make an error in the presence of distractors for the 3-target condition but were no more likely to make errors in the presence of distractors for either the 2-target or the 4-target conditions.

Comparisons of DI between these three conditions indicated there were no significant differences.

Comparisons suggested that DI for response times did not differ significantly between maintenance and updating conditions when participants had to remember 2 or 3 items, though it approached significance for the 2-target conditions, DI_{diff} = -27 ms, 95% CI [-60, 3]. The DI for the 4-target updating condition was significantly smaller than the DI of the 4-target maintenance condition, DI_{diff} = -126 ms, 95% CI [-158, -90]. Similarly, there were no significant error rate DI differences when comparing maintenance and updating tasks for each level of targets, though it approached significance when comparing the 2-target maintenance task to the 2-target updating task, DI_{diff} = 0.5 LOE, 95% CI [0.0, 0.9].

Figure 2.7 presents the DI across the RT distribution for Experiment 2 (see Figure A2 for an alternative delta plot similar to Experiment 1). As with Experiment 1, the 2-target updating condition showed a declining DI across the RT distribution. However, the 3-target updating condition showed a robust, *increasing*, DI across the entire distribution, similar to those seen in the maintenance conditions. In addition, the 4-target updating condition showed evidence of a "decreased" DI as RTs increased, such that RTs were *faster* in the presence of distractors compared to when distractors were absent.

2.9 DISCUSSION

Experiment 2 sought to replicate and extend the Experiment 1 finding that distractor interference can be mitigated by the participants' implementation of more stringent central executive selective attention processes when the task is sufficiently difficult, but only as long as there are sufficient remaining central executive resources not consumed by the primary working memory task. Our results show that the addition of a third and fourth target generated the hypothesized increase in task difficulty.

Experiment 1 data showed increased distractor interference as the number of targets increased during the maintenance task, leading us to suggest that participants may not have engaged selective attention processes for maintenance conditions because the task was easy, even with the addition of a second item. In Experiment 2, as with Experiment 1, distractor interference was present for all maintenance conditions. However distractor interference was equivalent across maintenance conditions regardless of the number of targets. These results are in line with our original hypothesis that the central executive is minimally involved with simple maintenance of information, which was handled by the phonological loop.

Unlike Experiment 1, distractor interference was equivalent for the 2-target updating and 2-target maintenance conditions (though the 95% CI suggests a trend towards smaller DI in the updating condition, as predicted). Increasing the number of targets for the updating task from 2 to 3 resulted in increased distractor interference for both response time and error rate. Our interpretation of these data is that up until the 3-target updating condition sufficient central executive resources were available for the central working memory task and selective attention. Increased DI for the 3-target updating condition compared to the 2-target updating condition suggest that central executive resources were largely consumed by the working memory task and that fewer resources could be put towards selective attention processes. If, as the data suggest, the 2-target updating condition is the inflection point after which there is a reduction in the availability of central executive resources for selective attention, any additional working memory load beyond 2 targets, in updating conditions, should have resulted in increases in distractor interference. Thus, distractor interference should have been largest for the 4-target updating condition. However, the 4-target updating task was completed at RTs similar to those seen during both the 2- and 3-target updating tasks and RTs and ERs were unaffected by the presence of distractors.

One possibility is that participants had to adopt a different strategy for the 4-back condition than for any other condition. The n-back task can be completed successfully using either familiarity based or recollection based processes (Kane et al., 2007). In the current experiment participants had to update an increasingly large sequence of letters but they still had only 3 seconds to respond on each trial. Verbally rehearsing this continuously changing sequence, i.e., using a recollection-based process, may have become too unwieldy and forced participants to rely on a familiarity-based process. This hypothesis is also consistent with anecdotal reports from virtually all of the participants, who reported having to do something “different” for the 4-target updating task – even if they couldn’t articulate how they were doing it differently.

The hypothesis that different processes may be engaged for the 4-target updating task is further supported by the analysis of distractor interference across the RT distribution, visualized in Figure 2.7. The 4-target updating task shows no distractor interference or *improved* response times in the presence of distractors across the entire distribution, which is unique when compared to all of the other experimental conditions. The implication is that both task demand *and* strategy selection is important when investigating interference effects. The idea that the choice of strategy for task completion affects the influence of distractors on task performance is not new. For example, visual search studies such as those conducted by Leber and Egeth (Egeth, Leonard, & Leber, 2010; Leber & Egeth, 2006) have proposed that the individuals can employ one of two search strategies: a) singleton search mode in which the “odd-item-out”, i.e., therefore the most salient item, is assigned the highest selection priority or b) feature search mode in which the individual assigns a certain feature as the highest selection priority. They found that when participants employed a feature search mode their visual search performance was unaffected by distractors that did not match the feature search mode template held in mind. In a similar vein, it could be the case that recollection-based strategies are more sensitive to distractors and more sensitive to changes in working memory load. This suggestion needs to be tested empirically.

Visual inspection of the quantile analyses conducted in both Experiment 1 and 2 (Experiment 1 - Figure 2.4 & Figure A1; Experiment 2 - Figure 2.7 & Figure A2) also suggest that there is something unique about the 2-target updating condition. Although the distractor interference effects in the 2-target condition were only smaller than the remaining conditions for Experiment 1, in both experiments distractor interference effects for the 2-target updating task got smaller across the RT distribution. In Experiment 1 we hypothesized that this reduced distractor interference could be, in part, a simple artifact of longer RTs for the 2-target updating task compared to all others. However, Figure A1 showed that even at similar RTs, the distractor effect was smaller for the 2-target updating condition than any other. Further evidence against reduced distractor interference simply as a function of longer RTs was seen in Experiment 2. The 3-target updating task had a similar RT distribution, in terms of raw response time, but unlike the 2-target updating task distractor interference effects *increased* across the RT distribution.

Thus, there is something unique about the 2-target updating task. This brings us back to our current proposal regarding the interactions between working memory and selective attention: there is an ‘optimal’ condition under which task difficulty is sufficient to invoke a more stringent top-down control mechanism *and* central executive resources are still available to implement this mechanism. Prior to a sufficient level of difficulty deployment of selective, top-down control mechanisms may be minimal. Once past this optimal level, as the resource requirements of the working memory task increase, central executive resources available for selective attention will decrease, resulting in increased distractor interference. Replication of the current results and further empirical testing of this theory is required.

2.9.1 LIMITATIONS

Although the use of the n-back task facilitated the independent manipulation of two different aspects of working memory, i.e., the central executive and the phonological loop there are some task limitations as it was implemented here. First, in distractor conditions the distractors were present both at encoding and at response. As a result it is currently unclear at what stage of processing distractor interference occurred. This could be attended to in future studies in which distractors are present at encoding or at response time but not both and could be accomplished by using versions of this task that do not require a response to every stimulus but make periodic demands of the participant to determine whether the current stimulus is the same as the target stimulus seen ‘n’ trials previously. Second, the current experiment only looked at loading the phonological loop but did not apply any independent load on the visuo-spatial sketchpad. Thus it is possible that distractor processing / inhibition may be, in part done by the visuo-spatial sketchpad rather than the central executive alone. It is also possible that the lack of distractor interference effects for the 4-back updating task was a result of switching to non-verbal recollection processes rather than familiarity processes, and the current data set is not well suited to distinguishing which may be true.

We chose to use inverted or rotated letters as “task-irrelevant” distractors in an effort to maintain equivalent target-distractor stimulus complexity. However, the current data along with an additional experiment in our laboratory (Weisskopp, Wilson, & Eskes, unpublished) suggest that these distractors may have been processed in the same manner as upright letters. That is, they were “read” in the same fashion as the targets. The result is that our distractor condition was the equivalent of incongruent target-distractor pairings similar to those found in the classic Ericksen and Ericksen paradigm. Similarly, the loss of the 1-target maintenance and updating conditions in the second experiment limits interpretability of these data, as we could not completely replicate the distractor interference found in Experiment 1. Replication of this experiment with upright, congruent, incongruent, and neutral target-distractor pairings along with the distractor absent conditions may make comparison easier between the current experiment and others that employ flanker tasks.

2.10 CONCLUSIONS

Despite its limitations, our data allow us to make a number of postulations about how we might better understand the effects of visual distractors on working memory performance under varying levels of working memory load. First, as with tasks such as visual search, the current data suggest that the magnitude of the distractor interference effect is not only task dependent, but also strategy dependent. Second, there appears to be a task-strategy interaction such that too easy a task results in minimal use of selective attention processes, optimal task difficulty results in allocation of central executive resources to both the central task and to more stringent application of selective attention processes, and that more difficult tasks result in central executive resources being prioritized for the central working memory task and application of the more stringent selective attention processes is no longer possible.

Table 2. 1

Mixed effects analysis of experiment 1 response time (RT) and error rate (ER) data.

Effect	RT	ER
distractors	612.04	2.40
# targets	1359.02	20.53*
task	2014.31	-0.28
distractors × # targets	-0.73	-2.89
distractors × task	32.34	-1.03
# targets × task	441.52	-2.41
distractors × # targets × task	30.13*	-2.86

Results are in Log-Base-2-AIC-Corrected Likelihood Ratios and are presented as ‘bits of evidence’. AIC = Akaike Information Criterion. * indicates highest order explanatory model

Table 2. 2

Mixed effects analysis of Experiment 2 response time (RT) and error rate (ER) data.

Effect	RT	ER
distractors	427.64	-1.04
# targets	174.20	187.37
task	1130.48	703.74
distractors × # targets	22.89	3.05
distractors × task	21.89	-2.72
# targets × task	83.07	33.01
distractors × # targets × task	55.19*	4.28*

Note. Results are in Log-Base-2-AIC-Corrected Likelihood Ratios and are presented as 'bits of evidence'; AIC = Akaike Information Criterion. * indicates highest order explanatory model

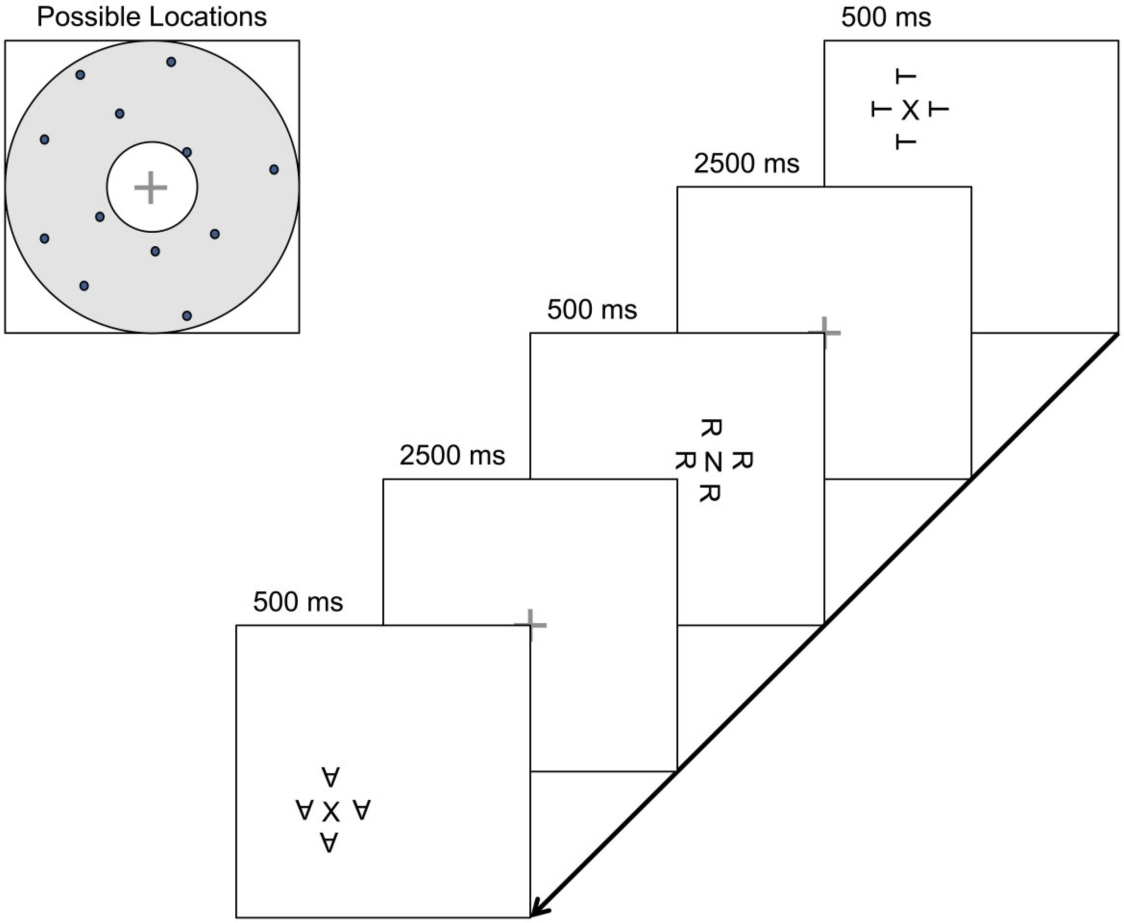

Figure 2. 1 N-back task. Participants were required to remember the letters, ignoring the location in which the letters appear and possible distractors (shown here) surrounding the target letter. Distractors appeared on 50% of the blocks of trials. On each trial subjects respond “yes” or “no” as to whether the letter corresponds to the “target” letter as dictated by the task type and level of n.

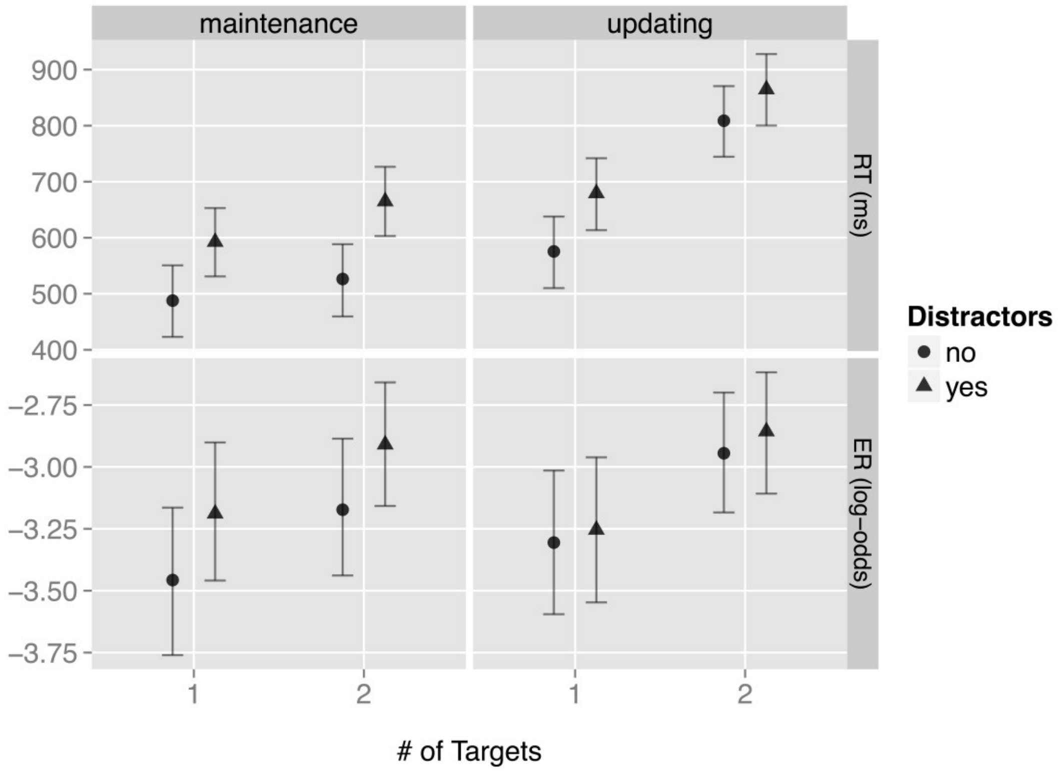

Figure 2. 2 Mean response time (ms) and error rate (log-odds base-2) for Experiment 1 maintenance tasks (1-target and 2-target maintenance) and updating tasks (1-target and 2-target updating). Error bars represent the 95% CI of the intra-subject variability (i.e., with inter-subject variability effectively zeroed).

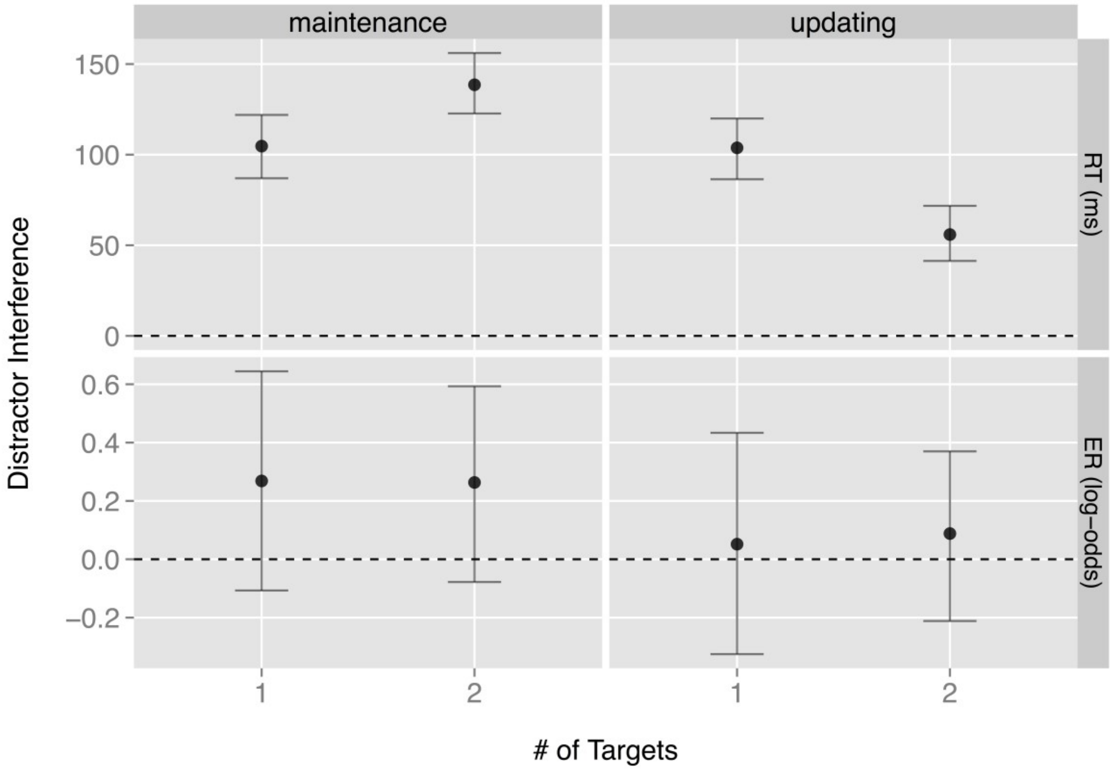

Figure 2. 3 Distractor Interference effects across conditions for Experiment 1. Distractor Interference (DI) is calculated as condition with distractors minus same condition without distractors. Error bars represent the 95% CI of the intra-subject variability (i.e., with inter-subject variability effectively zeroed). If the error bars do not cross 0 (dashed line), it is considered a significant DI for that condition.

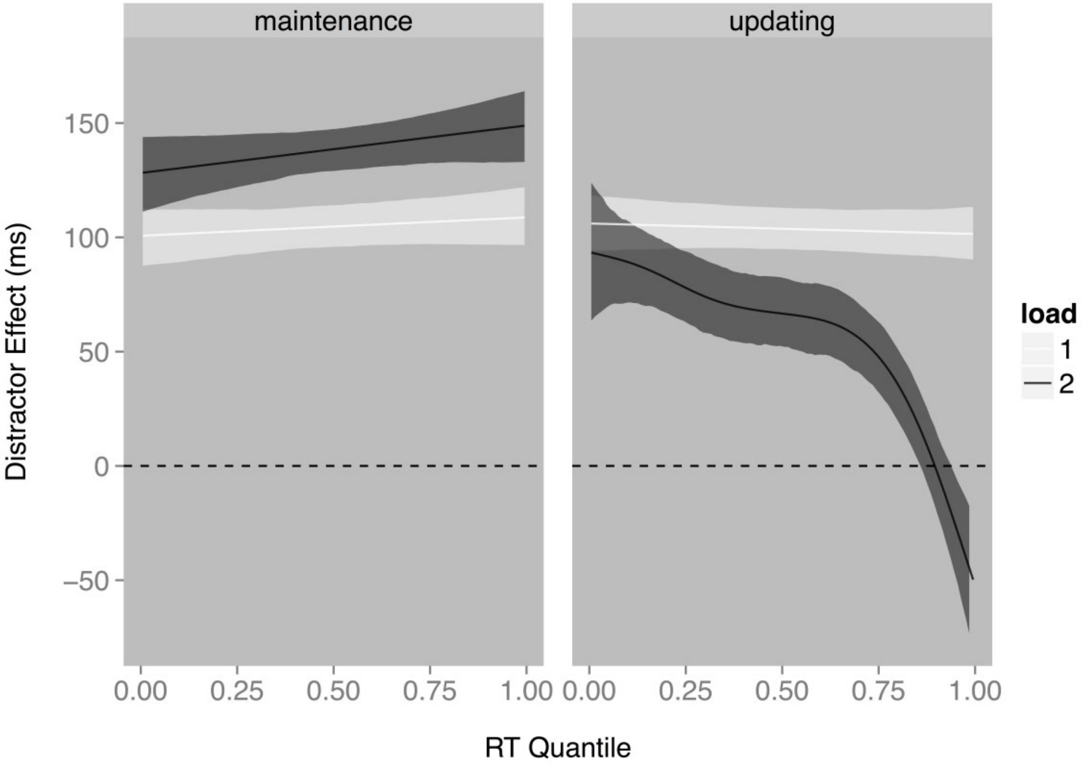

Figure 2. 4 Quantile plots examining distractor interference (DI) across the complete RT distribution by condition. Solid lines indicate predictions from Generalized Additive Mixed Models (GAMM) and shaded areas indicate 95% confidence intervals. As long as the confidence interval (shaded area) of a given condition does not overlap with the prediction (solid line) of the other condition, the difference is considered significant.

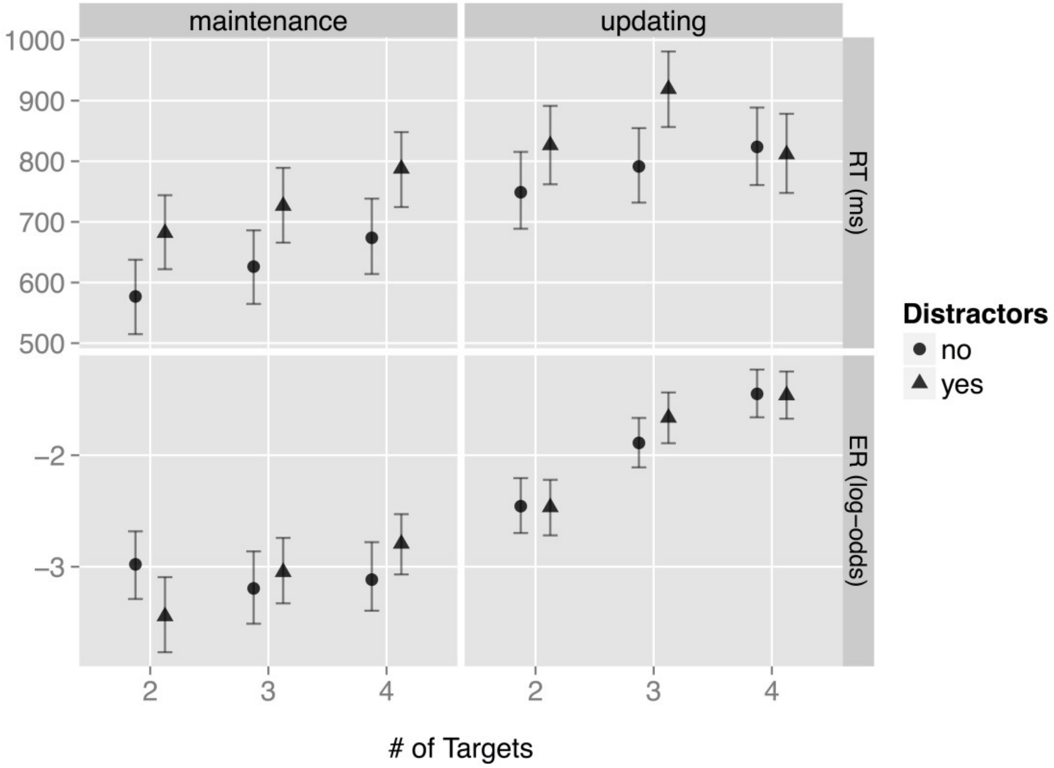

Figure 2. 5 Mean response times (ms) and error rates (log-odds base-2) for Experiment 2 maintenance tasks (2-, 3-, and 4-target maintenance) and updating tasks (2-, 3-, and 4-target updating). Error bars represent the 95% CI of the intra-subject variability (i.e., with inter-subject variability effectively zeroed).

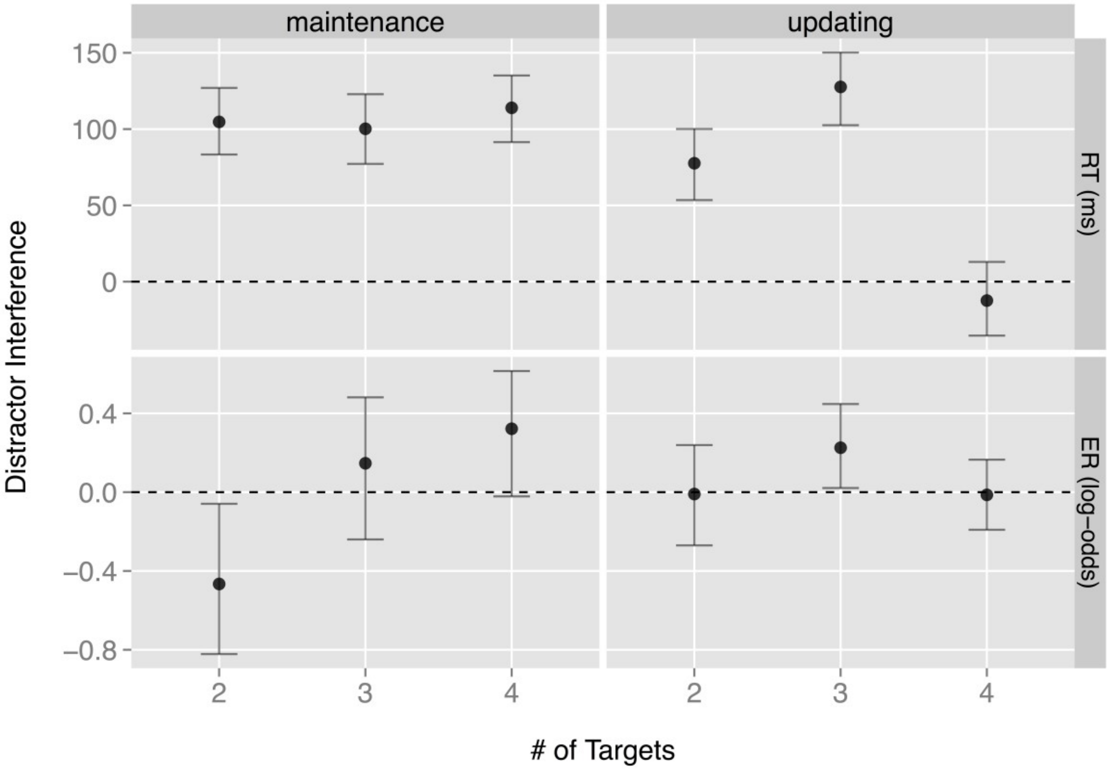

Figure 2. 6 Distractor Interference (DI) effects across conditions for Experiment 2. DI is calculated as condition with distractors minus condition without distractors. Error bars represent the 95% CI of the intra-subject variability (i.e., with inter-subject variability effectively zeroed). If the error bars do not cross 0, it is considered a significant DI for that condition.

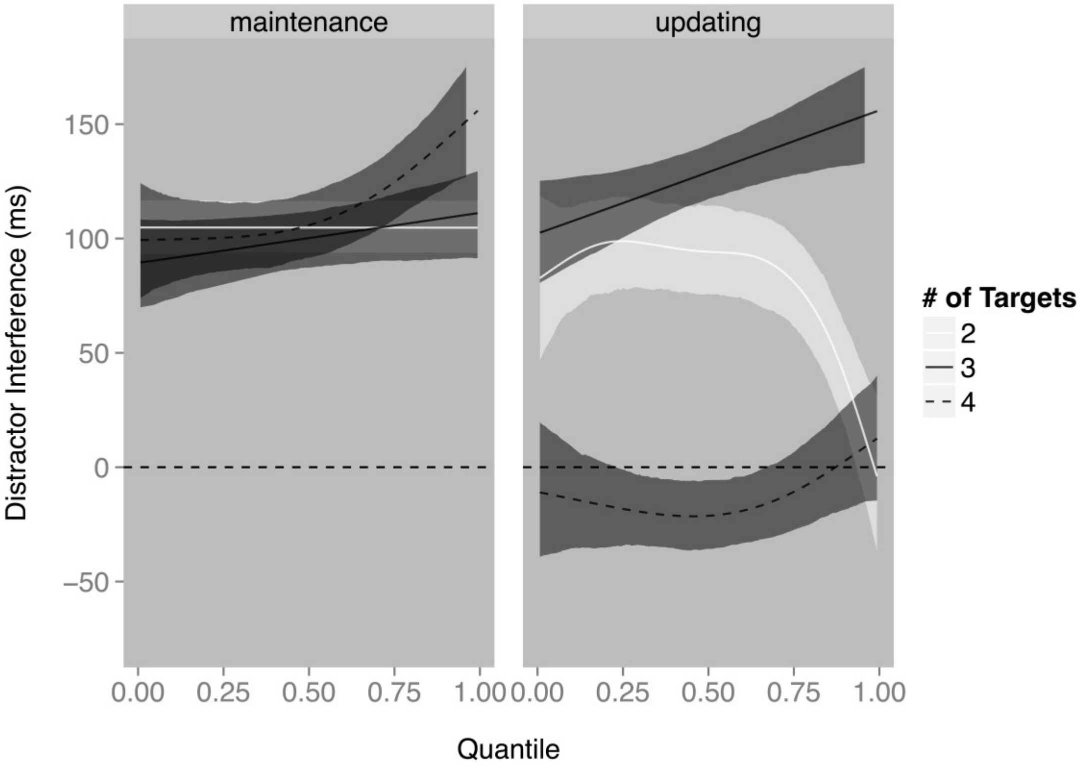

Figure 2. 7 Quantile plots examining the distractor interference (DI) across the complete RT distribution by condition in Experiment 2. Solid lines indicate predictions from Generalized Additive Mixed Models (GAMM) and shaded areas indicate 95% confidence intervals.

2.10 SUMMARY AND LINKING STATEMENT FOR CHAPTER 3

In Chapter 2 young adults exhibited slower response times for all levels of the n-back working memory task when distractors were present compared to when distractors were absent, supporting the hypothesis that the presence of distractors does have a negative effect on performance regardless of the working memory load. However, contrary to our predictions, distractor interference was smallest for the 2-target updating task. Our interpretation was that the 2-target updating task represented an optimal level of difficulty in which participants employed attention control mechanisms to filter task-irrelevant distractors to maximize performance on the working memory task.

In Chapter 3 we seek to extend these findings to samples from two novel populations: older adults and stroke survivors. Previous literature has suggested that older adults are more likely to have difficulties inhibiting task-irrelevant distractors (Hasher & Zacks, 1988) and this difficulty results in impaired working memory performance. In a similar vein, previous reports have proposed that attention and working memory are commonly affected in individuals who have vascular pathology, e.g., stroke survivors (Black, 2011). However, links between inhibition of distractors and working memory load (i.e., task difficulty) have not been well explored in aging and in vascular pathology. Thus, the goal of Chapter 3 is to examine the impact of distractors on working memory in these two populations.

CHAPTER 3 THE EFFECTS OF HEALTHY AND PATHOLOGICAL AGING ON TOP-DOWN CONTROL OF VERBAL WORKING MEMORY

3.1 ABSTRACT

Objectives: Deficits of top-down control (e.g., the ability to filter distractors) may contribute to cognitive decline in healthy aging. Furthermore, pathological aging (e.g., stroke) is often accompanied by additional attention and working memory deficits. In the current study we examined the effects of healthy and pathological aging on the top down control of attention during an increasingly difficult working memory task. We predicted that all participants would have greater difficulty coping with the presence of distractors as the task became more difficult and that stroke survivors would experience greater distractor interference (DI) effects than older adults. **Method:** Twenty healthy older adults and fifteen stroke survivors completed an increasingly difficult n-back with concurrently presented distractors on half of the blocks of trials. **Results:** Older adults and stroke survivors showed DI effects, but contrary to our predictions, DI effects were no greater for stroke survivors than they were for healthy older adults. Furthermore, both groups showed reduced DI effects for the most difficult task compared to all other conditions. **Discussion:** Our results replicate previous findings in healthy young adults (Wilson & Eskes, submitted) and support the theory that some aspects of top-down attention control may be preserved in healthy and pathological aging.

3.2 INTRODUCTION

Cognitive decline is common in otherwise healthy older adults and has implications for day-to-day living. Many older adults feel that this cognitive decline is one of the most difficult aspects of aging to cope with (Bayles et al., 1987). These difficulties can affect multiple cognitive functions, but changes are most frequently reported in processing speed, attention and memory, as well as executive function (Craik & Salthouse, 2000). In addition to cognitive decline in healthy aging, older adults are also at increased risk for vascular cognitive impairment (VCI), a syndrome that ranges from mild cognitive difficulties in a single domain to Vascular Dementia (Gorelick et al., 2011; O'Brien, 2006). VCI may be brought about by subclinical vascular pathology, such as small-vessel disease, or stroke (Gorelick et al., 2011), and research suggests that age is the single largest risk factor for stroke (Sacco et al., 1997). Individuals who have been affected by vascular pathology and stroke commonly experience attention and working memory difficulties (Black, 2011; Cicerone et al., 2000, 2011).

In the current study we examined the interactions between two specific cognitive processes thought to be affected by aging and stroke: working memory and attention control.

3.2.1 WORKING MEMORY

Working memory, or the ability to hold and manipulate information in mind, is regarded as a central process that provides a dynamic scratchpad for many goal-directed behaviours. Baddeley's model (Baddeley & Hitch, 1974; Baddeley, 2000) holds that working memory is a limited capacity system comprising material-specific maintenance systems for verbal and visuo-spatial information, the episodic buffer for the integration of currently activated information with long-term memory into integrated episodic representations, and the central executive – a capacity limited attention control system similar to Shallice's Supervisory Attention System (Shallice, 1988). In a recent meta analysis examining the executive components of working memory (Nee et al., 2013), the authors reported that despite a multiplicity of research proposing differing functional organizations of the central executive, all of the explanatory models of central executive function agree upon a set of key processes that include: shifting attention between information sets, updating the content of active information sets, and preventing distractors from interfering with optimal working memory performance, i.e., either through inhibiting the processing of task-irrelevant information or through resolving conflicts between stimuli.

3.2.2 TOP DOWN CONTROL IN AGING

In their influential model of aging, Hasher and Zacks proposed that age-related cognitive decline is a result of a failure to inhibit processing of task irrelevant information (Hasher & Zacks, 1988) Older adults are therefore most likely to encounter difficulties in tasks with interference, such as in the flanker task (Ericksen & Ericksen, 1974), a task in which optimal performance requires the individual to ignore incongruent flanking distractors while maintaining focus on the central targets (Weeks & Hasher, 2014). Indeed, data from numerous studies have supported Hasher's and Zacks' inhibitory deficit hypothesis in working memory tasks in which healthy older adults showed poorer performance on a variety of tasks with irrelevant distractors, such as in cases when distractors are temporally separated from the targets (Gazzaley, Cooney, Rissman, et al., 2005; Gazzaley et al., 2008; Gazzaley, Sheridan, Cooney, & D'Esposito, 2007), in discrimination tasks where the distractors and targets overlap (de Fockert et al., 2009; Quigley & Müller, 2014; Zanto et al., 2010) and in the aforementioned flanker tasks with surrounding distractors (Zhu et al., 2010). Gazzaley and colleagues have provided both behavioural and neurophysiological evidence (fMRI and EEG) for the inhibitory deficit in aging (eg., Gazzaley et al., 2008, 2005). For example, in their 2008 study, Gazzaley et al. had younger and older participants complete a working memory task in which they were presented with alternating faces and scenes. Participants then had to report on whether a delayed probe was a match to either the previously seen faces or scenes (depending on the instruction for that block of trials). These results were compared to a control condition consisting of passive viewing of similar faces and scenes followed by a simple discrimination task after the delay period. Older adults were less accurate in remembering both faces and scenes, although response times did not differ. Comparisons of event related potentials (e.g., P1 and N1) for both the to be remembered items and the to be ignored items against the passive viewing condition showed that both groups produced enhanced ERP amplitudes to task relevant stimuli (target – passive viewing) but in contrast, only younger but not older adults showed suppression of ERPs to task irrelevant stimuli (to-be-ignored – passive viewing). Thus, the authors posited that one mechanisms underlying worse working memory performance of the older adults was reduced ability to suppress task-irrelevant information (i.e., inhibitory deficit).

However, there appear to be some conditions under which older adults are no more affected by distractors than younger adults. Studies of visual search with distractors in aging (Costello et al., 2010), studies employing the Attention Network Task that includes a flanker task (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Ishigami & Klein, 2011; Jennings, Dagenbach, Engle, & Funke, 2007) and studies in which spatial selection of relevant stimuli can be employed (i.e., use of an ‘attentional window’) to constrain the distribution of visual attention (e.g., Quigley, Andersen, & Müller, 2012) have shown no or little effect of aging on task performance other than general slowing. In addition, although the aforementioned working memory studies by Gazzaley et al. (Gazzaley, Cooney, Rissman, et al., 2005; Gazzaley et al., 2008) reported an overall inhibitory deficit in aging, they also noted considerably more variability in the behavioural and neuropsychological data gathered from the older participants. This led them to subdivide the older adult group into ‘lower’ and ‘higher’ performing groups (median split). In both studies the lower performing but not the higher performing older adults showed the aforementioned suppression deficit relative to younger participants. Thus, the inhibitory deficit hypothesis may apply to some, but not all tasks, and some, but not all, aging individuals.

3.2.3 ATTENTION CONTROL IN STROKE

In addition to general cognitive decline with healthy aging, older adults are also at increased risk for vascular cognitive impairment (VCI), a syndrome that ranges from mild cognitive difficulties in a single domain to Vascular Dementia (Gorelick et al., 2011; O’Brien, 2006). VCI may be brought about by subclinical vascular pathology, such as small-vessel disease, or stroke (Gorelick et al., 2011), and research suggests that age is the single largest risk factor for stroke (Sacco et al., 1997).

Individuals who have been affected by stroke commonly encounter attention and working memory difficulties (Cicerone et al., 2000, 2011). Reports on the incidence rate of post-stroke attention deficits are as high as 45-92% in the acute phase of recovery (Stapleton et al., 2001) and although some of these deficits may resolve, attention difficulties are often chronic and significantly impact functional outcomes and activities of daily living. Post-stroke attention difficulties are evident on neuropsychological testing (e.g., (Hochstenbach et al., 2003; Hyndman et al., 2008; McDowd et al., 2003; Robertson et al., 1997; Stapleton et al., 2001) and self-reported measures of daily function (McDowd et al., 2003). Although these attentional difficulties appear to be most severe during the acute phase, i.e., up to 2 months post stroke (Barker-collo et al., 2009), residual attention difficulties are also likely to be chronic (Barker-collo et al., 2009; McDowd et al., 2003; Robertson et al., 1997).

A few studies have examined the impact of stroke on attention control processes (e.g., Lavie & Robertson, 2001; Rinne et al., 2013; Snow & Mattingley, 2006). Lavie and Roberston (2001) examined how unilateral neglect, a post-stroke condition in which individuals have a bias for attending to the ipsilesional visual space compared to the contralesional visual space, affected the extent to which individuals could ignore a congruent or incongruent flanking distractor while completing a speeded 2-forced-choice response task (i.e., whether an ‘A’ or a ‘B’ was presented in the center of the display. The results showed that when an incongruent flanker was presented to the ipsilesional visual space participants were significantly slower in responding on the central task than when the flanker was congruent. Conversely, when the flanker was presented to the contralesional space, no congruency effects were evident. Snow and Mattingley (2006) conducted a similar study in which unilateral neglect participants and healthy controls completed a speeded 2-alternative-forced-choice response task in which participants had to determine whether the centrally presented stimulus (a coloured letter) was the letter ‘A’ or ‘B’ (letter task), or whether the colour of the presented stimulus was red or green (colour task), while ignoring flankers that could be congruent or incongruent on one (i.e., colour or letter) or both dimensions (colour and letter). Flankers were presented on either the ipsilesional or contralesional side. Healthy controls showed flanker interference effects (i.e., slowed response times when an incongruent distractor was present) regardless of the position of the flanker, but only for the task relevant domain, i.e., if the task was letter identification only incongruent letter identities produced flanker interference effects. Conversely, neglect participants showed flanker interference effects for both task-relevant and task-irrelevant domains (i.e., both colour and letter) when flankers were presented to the ipsilesional side. In addition, neglect participants showed flanker interference effects when distractors were presented to the contralateral side, but only for the task relevant domain (i.e., colour or letter). These results suggest that information in the contralesional space may still be processed in neglect and that attention control processes may be adversely affected by stroke even in ipsilesional space, an aspect of attention control that was previously thought to be preserved.

The two studies discussed in the previous paragraph focused on a very specialized subset of the stroke population. However, as discussed above, it appears attention control difficulties may be present in the broader stroke population. Rinne and colleagues (2013) compared the performance of patients with an acute stroke to healthy controls on the ANT measuring the 3 separate attention networks: alerting, orienting, and executive function. Sub-analyses of the patient group (N = 102) revealed dissociable deficits in each of the 3 attention networks based on lesion location. The relevant finding for the current study is that, behaviourally, although stroke participants were slower and less accurate than healthy controls, there were no interactions between group membership and measures of alerting, orienting, or executive control, suggesting preservation of some aspects of attention control in stroke as a whole.

Overall, the data described here are equivocal with respect to the extent to which stroke, an example of vascular cognitive impairment, might affect attentional control. The data do support greater impairment of attentional control based on lesion location, e.g., right hemisphere stroke in the case of unilateral neglect (Rinne et al., 2013). However, it remains unclear how increased working memory demands might further impact attentional control processes in stroke populations.

3.2.4 CURRENT STUDY

Examination of the evidence reviewed here suggests that task demands may be a factor in the discrepancies in the literature. Visual search and flanker tasks such as the ANT emphasize attention control but place little extra burden on working memory mechanisms (e.g., information storage). In contrast, the studies that showed inhibitory deficits in aging required both attentional control and holding information in mind to generate a response. This leads us to question whether distractor interference effects may differ as a function of working memory load as posited by de Fockert et al. both in healthy young (de Fockert et al., 2001; Wilson & Eskes, 2014), in aging (de Fockert et al., 2009) and by extension stroke survivors.

For example, in our previous work (Wilson & Eskes, 2014) we examined the effects of distractors and working memory load on working memory performance in healthy young adults using the n-back paradigm. The typical n-back paradigm is a two-alternative-forced-choice response task in which participants must determine whether a currently presented stimulus within a sequence is a match or a mismatch to a target(s) held in mind(Owen et al., 2005). The target can either remain the same throughout the sequence (e.g., the 0-back condition), or it can change with each subsequent stimulus (1 or 2-back conditions). The typical 0-back condition requires participants to hold in mind (i.e., *maintain*) the first stimulus presented as the target and determine whether each proceeding item is a match with the target. We added a second 0-back condition in which participants had to maintain the first *two items* of the stimulus set and determine whether the current stimulus was a match for either of the two targets. In contrast, 1- or 2-back conditions require both maintenance and *updating* of the working memory store because the participant must determine whether the currently presented stimulus is a match to the stimulus presented 1 or 2 trials ago. Use of these conditions allowed us to compare response time and error rate performance on tasks requiring minimal additional executive processing (i.e., maintenance conditions) to tasks requiring more executive processing (i.e., updating conditions) while controlling for the number of targets that had to be held in mind (1 vs. 2). Participants completed the same tasks in both distractor present and distractor absent conditions in order to obtain a measure of distractor interference. We hypothesized that when central executive processing requirements were minimized, distractor effects would be small because central executive resources would be available to inhibit distractor processing (i.e., top down attention control). When central executive resources were consumed by the task (i.e., in updating conditions) we predicted that participants would be less able to ignore the distractors, resulting in greater distractor interference. Contrary to our predictions, the results showed that distractor interference was smallest in the 2-back condition compared to all other conditions. Our conclusion was that, unlike the maintenance and 1-back conditions, the 2-back condition was sufficiently difficult to induce participants to employ additional attention control processes. Participants still had sufficient central executive resources available to inhibit processing of distractors and to facilitate task performance.

The purpose of this experiment was to examine the effect of concurrently presented distractors on the performance of older adults and stroke survivors on an increasingly difficult working memory task. To this end, we used the previously described version of the n-back (Wilson & Eskes, 2014) to independently assess the effects of task (maintenance vs. updating), number of targets (1 vs. 2), and distractors (present vs. absent) on working memory performance of healthy older adults and a group of stroke survivors in the chronic post-stroke stage (i.e., > 2 months post stroke).

3.2.5 HYPOTHESES

As with our previous study, we predicted that manipulations of the number of targets variable (i.e., increasing the number of targets) and task variable (i.e., changing from a maintenance task to an updating task) would result in increased response times and error rates as the task became more difficult.

Based on the inhibitory deficit theory of cognitive aging we hypothesized that older adults would show a different pattern of response to the presence of distractors than did the healthy younger adults previously tested. Thus, we predicted that increasing the number of targets in the updating condition would further strain central executive processes making it more difficult for the older adults to inhibit processing of the distractors, and would result in greater distractor interference effects as the number of targets increased in the updating task.

With respect to differences between healthy older adults and stroke survivors, the attention and working memory deficits that often accompany stroke suggest that individuals who have had a stroke should have more difficulty with working memory tasks in general (although see Ziemus et al., 2007 in which cerebellar stroke survivors had equivalent behavioural performance to age matched controls on the 0-back and 2-back working memory tasks) and more difficulty coping with task irrelevant distractors than healthy older adults. Therefore, we predicted that: a) stroke survivors would be slower and less accurate on the working memory tasks than the healthy older adults, b) stroke survivors would be more adversely affected by the presence of distractors than older adults across all conditions, and c) because central executive processes are theoretically a more scarce resources in individuals who have had a stroke, stroke survivors would experience greater distractor interference effects than did older adults as working memory load increased during the updating tasks.

3.3 METHOD

3.3.1 PARTICIPANTS

Twenty healthy older adults and seventeen stroke survivors were community volunteers from Halifax, NS, Canada. Inclusion criteria required all healthy control participants to be between the ages of 55 and 90 years old, with no self-reported history of loss of consciousness, and have no other medical history that may affect cognitive functioning (e.g., neurological disorders such as MS or epilepsy and psychiatric disorders such as depression or anxiety). Inclusion criteria for stroke group participants required them to be: between the ages of 55 and 90 years old, at least 3 months post-stroke, able to complete informed consent, and no other medical history that may affect cognitive functioning. All participants were, by self-report, right-handed. Of the seventeen stroke group participants included in this experiment, one participant chose to withdraw from the study and one participant did not demonstrate adequate understanding of the task – performing at chance levels for all conditions. As a result, analysis was conducted on the performance of twenty healthy controls and fifteen stroke survivors. There were no significant differences with respect to age or education, but there were more male participants in the stroke group than the healthy older adult group (see Table 3.1 for a breakdown of demographics).

Participants received a small honorarium (at a rate of $10 per hour) for completing the study. This research was reviewed and approved by the Research Ethics Boards of the Capital District Health Authority. Informed consent was obtained in writing from all participants.

3.3.2 APPARATUS AND STIMULI

Task apparatus and stimuli were identical to those used by Wilson and Eskes (submitted). Briefly, target letters (capital A through Z) and distractors (inverted and/or rotated letters – A through Z except: N, O, V, W, and Z) were presented on a 27-inch screen. Participants were seated at a viewing distance of 60 inches so that letters and distractors were approximately 1 X 1 degree of visual angle and when present, distractors were placed 1 degree of visual angle immediately above, below, to the left, and to the right of the central target (see Figure 3.1).

3.3.3 TASK

The task was identical to the one used by Wilson and Eskes (submitted). Briefly, participants completed an n-back task in which they had to determine whether the presented letter was a target letter by responding “yes” or “no” via mouse button presses (left button = match, right button = mismatch). Stimuli were presented for 500 ms with a

2500 ms inter-stimulus interval. Each participant completed at total of 24 blocks of trials. All participants completed the tasks in the following order: 1-target maintenance (distractors absent), 1-target maintenance (distractors present), 2-target maintenance (distractors absent), 2-target maintenance (distractors present), 1-target updating (distractors absent), 1-target updating (distractors present), 2-target updating (distractors absent), and 2-target updating (distractors present). Thus, in half of the blocks of trials, participants also had to ignore distractor stimuli (i.e., inverted, or mirror-reversed letters) that were presented concurrently with the target stimulus (4 distractors placed symmetrically at a distance of 1 degree of visual angle from the target). Stimuli could present at one of 12 locations on the screen. This was done so participants would not be able to adopt a "tunnel vision" strategy (i.e., hyper-focus on the center of the screen) and the attentional control would have a greater likelihood of needing to be engaged on each trial. See Figure 3.1 for an example of a typical trial.

3.3.4 PROCEDURE

All participants were tested individually in one 75-minute session. Participants completed one block of practice trials for each task, and were provided with auditory feedback (bell = correct, buzzer = incorrect). They then completed two test blocks of test trials for each condition, with no feedback. All conditions consisted of 20 match trials and 20 mismatch trials. Additionally, 12 lure trials (i.e., 20% of trials), in which the currently presented stimulus was a match to n-1 but not n-2, were added to the 2-target updating condition to minimize participant reliance on a familiarity-based recognition strategy.

3.3.5 STATISTICAL ANALYSIS

Generalized Linear Mixed Models (GLMMs; Pinheiro & Bates, 2000) were employed to analyze the response time (RT) and error rate (ER) data, using distractors (absent vs. present), targets (1 vs. 2), and task (maintenance vs. updating) and group (controls vs. stroke) as effects of interest. Please see Lawrence and Klein's recent work for a review of the benefits of treating response time and error rate data using mixed effects (Lawrence & Klein, 2012). A full description of the model analysis employed here (also as in Lawrence & Klein, 2012; Wilson & Eskes, submitted) can be found in the Supplementary Materials or in the aforementioned papers.

The final model analyses are presented here as "bits of evidence" using the log-base-2 scale, and any resulting bits of evidence greater than 3 was deemed a significant finding. Post-hoc comparisons between the various conditions we completed using point estimates and 95% confidence intervals a posteriori bootstrapping methods[3].

3.3.6 DATA PRE-PROCESSING

As a result of 4 healthy controls and 1 stroke group participant not following instructions for some blocks of trials a total of 240 trials were removed from the analysis. Trials with a response time less than 200 ms were also removed from the analysis (< 1% of trials).

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[3] Readers will note that the use of point estimates (PE) and confidence intervals (CI) generally makes reporting an effect size somewhat redundant from the point of view that effect sizes are generally meant as a measure of the signal-to-noise ratio and confidence intervals provide the same information, albeit in a slightly different presentation. Those interested in an effect size like measures might find an equation such as 2*PE/CI a useful estimator for the effects reported here.

3.4 RESULTS

Figure 3.2 provides a visualization of the point estimates and 95% Confidence Intervals (of intra-subject variability) of both correct response times and error rates for both groups in all conditions (see Table 3.2 for model analysis).

3.4.1 EFFECT OF TASK AND TARGETS ON WORKING MEMORY PERFORMANCE

Response time (RT) performance data best fit the significant 3-way interaction of distractors × number of targets × task (Table 3.2), however we first examined the significant number of targets × task interaction collapsed across groups to ensure we observed the desired increases in task difficulty. As predicted, response times were shortest for the 1-target maintenance condition, RT = 702 ms, 95% CI [667, 735], longer for the 2-target maintenance condition RT = 776 ms, 95% CI [742, 812], longer still for the 1-target updating condition RT = 812 ms, 95% CI [777, 847], and longest for the 2-target updating condition RT = 1234 ms, 95% CI [1199, 1270]. Targets and task interacted such that the addition of a second target to the updating condition led to a significantly greater response time increase, RT_{diff} = 422 ms, 95% CI [409, 433] than did adding a second target to the maintenance condition, RT_{diff} = 75 ms, 95% CI [63, 87].

Analyses also supported a significant 2-way interaction of targets × task on error rates. As predicted, participants were least accurate for the 2-target updating task, ER = -1.6 log-odds of error (LOE) [4], 95% CI [-1.8, -1.4], when compared to all other conditions, which did not differ significantly from each other. Overall, our data support successful manipulation of targets and task to create increasingly difficult working memory tasks.

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[4] The “log-odds of error” scale has the following equivalence on the proportional scale: 0 represents an error rate of 50%, –1 represents an error rate of about 27%, –2 represents an error rate of about 12%, and –3 represents an error rate of about 5%.

3.4.1.1 Between group differences

There was a significant group × task interaction for both RT (bits = 14) and ER (bits = 28). For maintenance tasks, older adults were slightly faster, RT = 712 ms, 95% CI [670, 759], than stroke group participants, RT = 766 ms, 95% CI [716, 818]. Response times were comparable for the older adults and stroke group for the updating conditions, RT = 1009 ms, 95% CI [968, 1057] and RT = 1030 ms, 95% CI [980, 1081] respectively.

Error rates showed the identical pattern of results. Thus, contrary to our predictions, older adults had better performance for the easier, maintenance tasks compared to stroke group participants but the two groups performed at equivalent response times and error rates for the more difficult updating tasks.

3.4.2 EFFECT OF DISTRACTORS ON WORKING MEMORY PERFORMANCE

Examination of the distractors × group × number of targets × task interaction revealed that distractor interference effects were not significantly different when comparing both response times and error rates of older adults and stroke survivors. To aid in the interpretation of the 3-way interaction of distractors × number of targets × task (collapsed across group), distractor interference (DI) effects were calculated as follows:

$$\mathrm{DI} = \text{condition (distractors present)} - \text{same condition (distractors absent)}$$

Therefore, distractor interference (DI) reflects the average amount of additional time needed to complete a task in the distractor present compared to distractor absent conditions. DI effects were visualized for both groups in Figure 3.2 but for purposes of discussion the data are collapsed across groups. As predicted, DI was evident for both maintenance conditions and did not differ whether there was one target, DI = 137 ms, 95% CI = [121, 154] or two targets, DI = 147 ms, 95% CI [-130, 163]. However, contrary to our predictions, distractor interference was smaller for the 1-target updating condition DI = -113 ms, 95% CI [97, 130], than for the 1-target maintenance task or the 2-target maintenance task. Furthermore, contrary to our current hypotheses but consistent with our previous findings in healthy young adults (Wilson & Eskes, 2014), distractor interference for older adults and stroke survivors was smallest for the 2-target updating condition DI = 31 ms, 95% CI [15, 47] when compared to all other conditions. Finally, the presence of distractors did not influence error rates.

3.4.2.1 DI over the full RT distribution

As in our previous study (Wilson & Eskes, 2014), we felt it important to consider the possibility that distractor interference effects might diminish with increased processing time. It is possible that the decreased DIs observed in the updating tasks could have been a result of the relatively longer overall response times for those conditions. We therefore examined the DI across the RT distribution through the use of quantile analysis (for a detailed description of the analysis see Lawrence & Klein, 2012; Wilson & Eskes, submitted). Figure 3.4 displays the DI effect across the total response time distribution collapsed across groups. Visual inspection of Figure 3.4 suggests that the DI increased with longer response times for both 1-target and 2-target maintenance conditions and that the two conditions did not differ at any point in the distribution. The DI for both the 1- and 2-target updating tasks did decrease overall with longer response times but the DI for the 2-target updating task was always significantly smaller than for the 1-target updating task, even at the fastest RTs. Thus, similar to our previous findings, although smaller DIs may be partly attributable to longer response times, significant differences particularly at the earliest portion of the response time distribution suggest that DI differences between conditions cannot be wholly attributed to the longer RTs. See Appendix B for delta plots similar to those seen in Chapter 1 that show DI as a function of RT.

3.5 DISCUSSION

Our objectives were to examine the extent to which visual distractors might affect performance on an increasingly difficult working memory task in older adults and stroke survivors. Manipulations of the task variable (maintenance vs. updating) and targets variable (1 vs. 2 targets) resulted in the expected increases in RT and ER for both groups. Unexpectedly, although stroke participants were slower and made more errors than healthy older adults during the maintenance tasks, they performed at equivalent RTs and ERs to healthy controls for the more difficult updating tasks.

Based on the inhibitory deficit theory of cognitive aging we postulated that older adults would have greater difficulty with distractors in updating conditions compared to maintenance conditions, resulting in greater distractor interference and therefore further increases in response times and erorr rates. We also predicted that stroke survivors, a group characterized by attention and working memory difficulties, would have even greater difficulties than older adults filtering irrelevant distractors as task difficulty increased. However, we found no evidence for either of these predicted increases in distractor interference effects.

3.5.1 EFFECTS OF DISTRACTORS IN AGING AND STROKE

Our primary objective was to assess the impact of distractors on working memory performance in older adults and stroke. Our data suggest that healthy controls and a heterogeneous stroke population respond to the presence of task irrelevant distractors in a similar fashion. Distractors affected the response times of both groups in the same way regardless of working memory load. For relatively simple maintenance tasks, distractors produced significant slowing in response times for the central tasks. As the task became more difficult, i.e., an updating task, the effect of distractors was still present, but was smaller when compared to the maintenance task and continued to decrease as the task became more difficult (i.e., comparing 1-back and 2-back conditions).

Although not our primary objective, in Experiment 1 of a separate manuscript (Wilson & Eskes, 2014) we assessed the impact of distractors on the working memory performance of healthy young adults using identical procedures. Thus, we are in a position to assess how age might play a role on the impact of distractors in working memory performance.

Overall, as would be expected, younger adults were faster and more accurate than either the older adults or the stroke group who did not differ from each other (See Supplementary Analysis). The addition of a second target to the updating condition had a much smaller effect on the performance of younger adults than older adults or stroke group participants. However, the distractor and group variables did not interact, thus the distractor interference effects presented here and in our previous work hold true regardless of age and stroke status.

Thus, it appears that some aspects of selective attention are preserved in aging and in the chronic stages of stroke. Our data support findings that selective attention may be preserved for tasks such as visual search (Costello et al., 2010) or in cases where spatial selection processes can be used to filter task-irrelevant distractors (Quigley et al., 2012). Gazzaley et al. (Gazzaley et al., 2008) also demonstrated that some older adults performed as well as younger adults on working memory tasks when distractors were presented in the maintenance phase. Thus, under certain conditions some older adults may be able to maintain top-down attentional control in a manner similar to young adults.

Similarly, our stroke group was in the post-acute stage and had a heterogeneous, self-reported localization of the stroke. When considered in the context Rinne et al. (2013), in which the stroke group as a whole exhibited no additional executive deficits compared to controls on the flanker task, and behavioural results from Ziemus et al. (Ziemus et al., 2007), who showed no behavioural differences in 0-back or 2-back performance it appears these top-down control processes may be preserved in stroke as well. However, this latter postulation should be interpreted cautiously as both Rinne et al. and Ziemus et al. had well described neuroimaging and localization of the stroke groups and subsequent sub-analyses did reveal differences in executive control (Rinne et al., 2013) based on lesion location. One final consideration is that we may not have reached the working memory capacity limits in the current set of experiments. If our theory is correct, namely that the use of top-down attention control to filter distractors only occurred when the task was most difficult, then that implies that even though older adults and stroke survivors found the task more difficult, both groups still had sufficient central executive resources to apply distractor filtering. We did not explicitly measure working memory capacity of our participants as others have done (e.g., Unsworth & Engle, 2005) and so cannot know for sure. Future studies of this nature may benefit from the use of this additional measure.

3.5.2 LIMITATIONS

There are a number of limitations with the current study. First, issues regarding paradigm selection mirror those found in our study using the n-back to examine distractor interference effects in healthy young (Wilson & Eskes, 2014). Presenting distractors with every target meant we were unable to tease apart whether the distractor interference produced in the current study occurred during encoding, retrieval, or during response generation. It would be useful to examine whether healthy older controls and stroke participants were filtering distractors at the encoding stage versus resolving the response conflict at post-perceptual stages as efficient filtering at the encoding phase would not be predicted based on Hasher and Zacks theory of cognitive aging (Hasher & Zacks, 1988).

There are additional limitations regarding our recruitment of participants. Our stroke group participants were highly motivated, well educated individuals and may not be a representative sample of stroke survivors in the general public, thus limiting generalizability of the current results. In addition, we did not collect information on stroke localization or size, which make it difficult to compare our results to studies such as the one conducted by Rinne et al. (2013).

Finally, although the task clearly became more difficult, it could be the case that 2-target updating condition was still not difficult enough to deplete working memory resources to the point where selective attention processes became compromised. Follow-up with a study similar to Experiment 2 in our previous study would further extend our current findings (Wilson & Eskes, 2014).

3.6 CONCLUSION

This experiment represents a replication of our primary findings in Wilson and Eskes (submitted). When a working memory task is easy attentional control mechanisms are either not at all or minimally engaged. As the task becomes more difficult, attention control mechanisms are brought online to minimize the impact of task-irrelevant distractors. The current study extended our previous findings by demonstrating that healthy older adults and stroke survivors are able to apply more stringent top down filters to protect the contents of working memory from intrusions by concurrently presented task-irrelevant stimuli in a similar fashion to healthy young adults.

Table 3.1 Demographic information of controls and stroke group participants

	Controls ($n = 20$)	Stroke ($n = 15$)	Differences
age (in years)	70.3 (10.1)	65.0 (6.90)	*n.s.*
# of males	3	7	$p < .05$
education (in years)	15.8 (2.8)	13.7 (2.8)	*n.s*
months since stroke	-	67.4 (57.5)	*n.s.*
hemisphere of stroke	-	LH - 8	
		RH - 3	
		BL - 3	
		BS - 1	

Note: S.D. in parentheses. LH = left hemisphere, RH = right hemisphere, BL = bilateral, BS = brain stem

Table 3. 2 Analysis of response times and error rates of healthy older adults & stroke group participants

Effect	Response Times*	Error Rates*
distractors	642.05	0.84
group	1.93	-2.85
# targets	3287.83	586.40
task	4446.43	549.24
distractors × group	-2.69	-2.40
distractors × # targets	12.19	-1.81
distractors × task	67.05	-2.88
group × # targets	-1.75	0.67
group × task	14.04	28.19*
# targets × task	2232.92	145.95*
distractors × group × # targets	-2.52	-1.82
distractors × group × task	-2.87	-2.60
distractors × # targets × task	40.64*	-2.11
group × # targets × task	-0.78	-0.13
distractors × group × # targets × task	1.63	-2.75

*Note. *Results Reported Using Log-Base-2-AIC-Corrected Likelihood Ratios as 'Bits of Evidence' AIC = Akaike information criterion.*

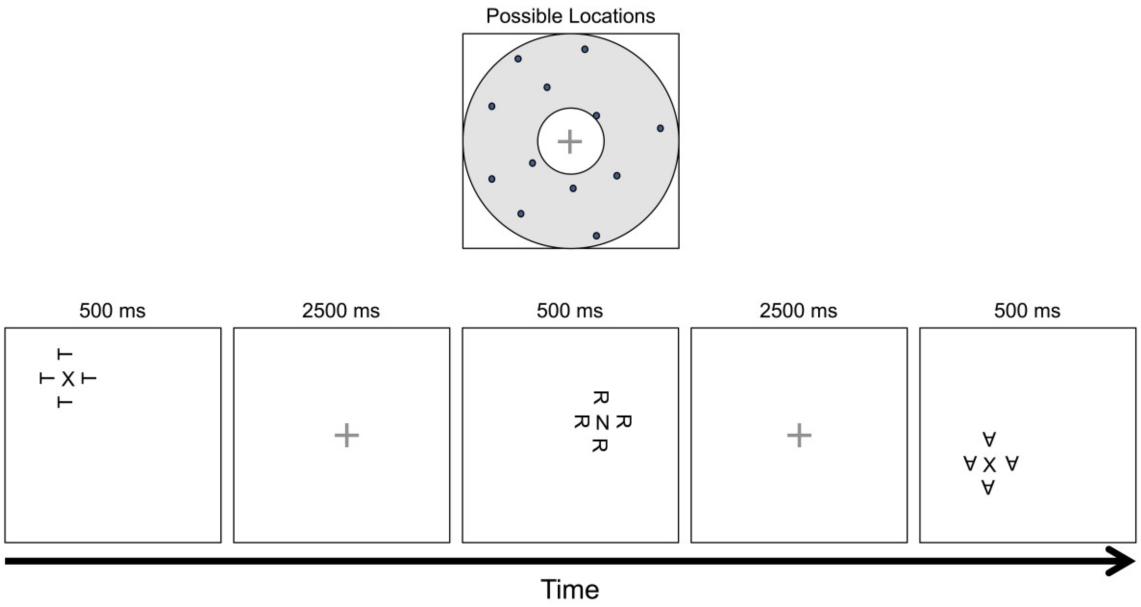

Figure 3. 1 N-back task. Participants were required to remember the letters, ignoring the location in which the letters appear and possible distractors (shown here) surrounding the target letter. Distractors appeared on 50% of the blocks of trials. On each trial subjects respond “yes” or “no” as to whether the letter corresponds to the “target” letter as dictated by the task type and level of n.

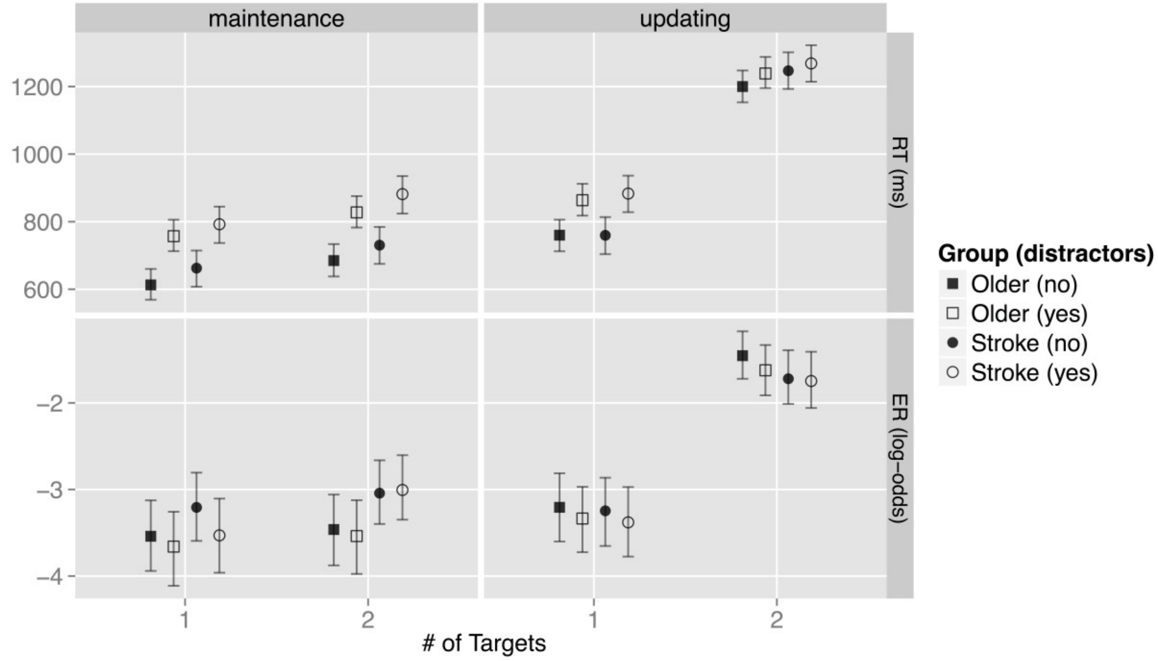

Figure 3. 2 Visualization of response time and error rate data for healthy older adults and stroke group participants. Error bars represent 95% CI for each point estimate as detailed in the Statistical Analysis section.

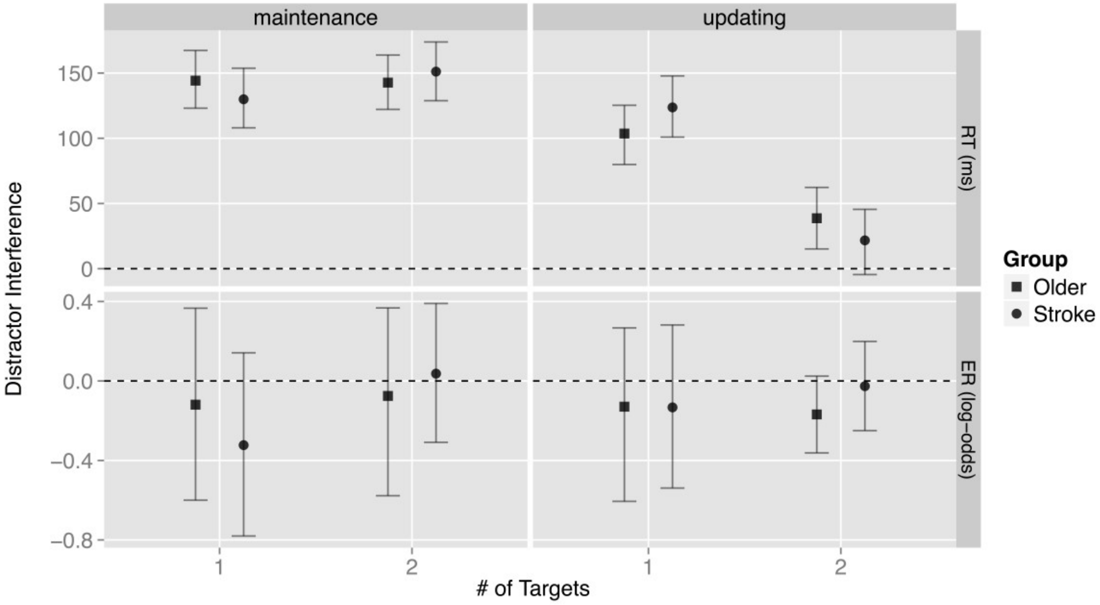

Figure 3. 3 Distractor interference effects across conditions for healthy older adults and stroke group participants. Distractor Interference (DI) was calculated as condition with distractors minus same condition without distractors. Error bars represent the 95% CI of the intra-subject variability (i.e., with inter-subject variability effectively zeroed). If the error bars do not cross 0 (dashed line), it is considered a significant DI for that condition.

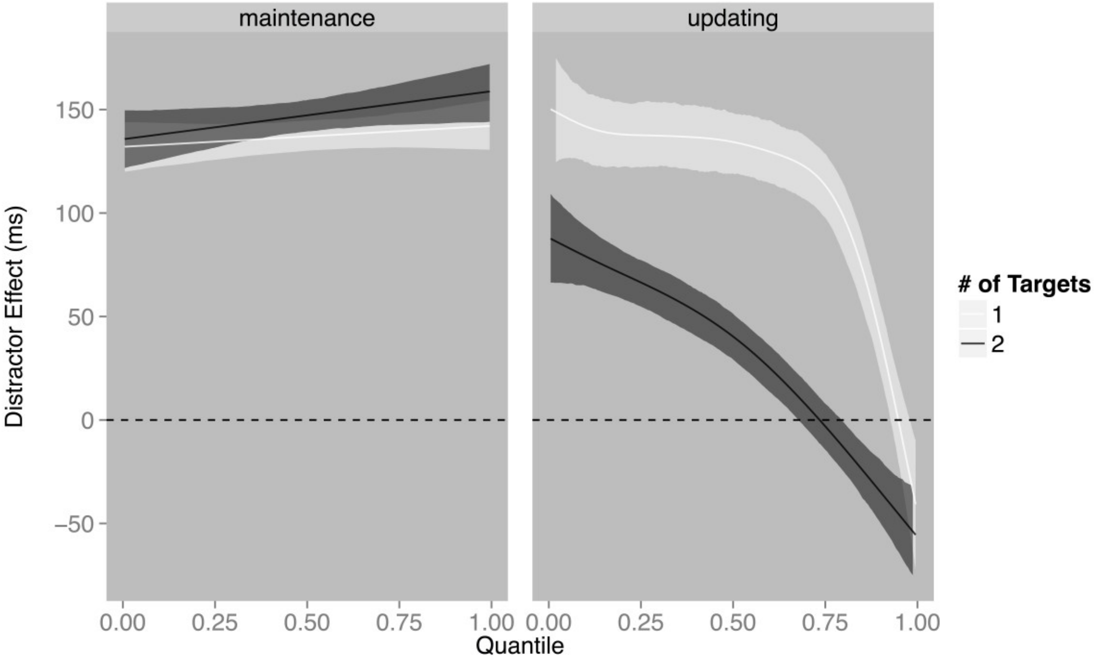

Figure 3. 4 Distractor Interference (DI) effects across the response time distribution. Solid lines indicate predictions from Generalized Additive Mixed Models (GAMM) and shaded areas indicate 95% confidence intervals. The DI was the same for 1- and 2-target maintenance conditions across the entire distribution. DI decreased over time for both the 1- and 2-target updating conditions but remained consistently smaller for the 2-target updating condition than for the 1-target updating condition across the entire distribution.

CHAPTER 4 GENERAL DISCUSSION

4.1 DISCUSSION OVERVIEW

The overarching goal of this dissertation was to examine the interaction between two closely related constructs, working memory and attentional control. Attentional control, the ability to filter task-irrelevant information, is thought to play a key role in optimal working memory performance and has previously been shown to be compromised in healthy and pathological aging (i.e., stroke). Three primary hypotheses were put forward: a) all participants would show Distractor interference effects (DI), b) all participants would show greater DI effects as the working memory task became more difficult, and c) DI effects would be smallest for younger adults and greatest for stroke survivors, while DI effects for older adults would fall somewhere in between these two extremes. Chapter 2 examined how the presence of concurrent distractors affected working memory performance of healthy young participants on an increasingly difficult task across two experiments. Chapter 3 extended these findings by examining the impact of distractors on the working memory performance of healthy older adults and stroke survivors on this same task. Strengths and limitations of the currently used paradigm as a whole, along with implications for future research will also be discussed.

4.2 MANIPULATIONS OF TASK DIFFICULTY

Working memory tasks in every day life (e.g., mental arithmetic, reading conversing) had differing degrees of difficulty as a result of the number of unique chunks of information that have to be considered or the complexity of the operation has to be carried out. However, as discussed extensively, it has a finite capacity and it is therefore important to have other mechanisms, such as attentional control, in order to protect the contents of working memory to ensure optimal performance. The dissertation objectives were to understand how the efficiency of attentional control processes would change as a function of working memory load and what the resultant impact of the changes in attentional control efficiency might mean for working memory performance. Given that the goal of this research was to examine distractor interference effects across variable working memory loads it was important to ensure that manipulations of number of targets and task type produced the were in fact making the working memory task more difficult before examining distractor interference.

In general manipulations of number of targets (1, 2, 3, or 4) and task (maintenance vs. updating) produced the anticipated reductions in task performance (i.e., longer response times or increased error rates). Supplementary analysis for Chapter 3 (see Appendix B) examined the differential effects of load manipulation as a function of group: younger adults, older adults, and stroke survivors. With respect to response times, all participant groups experienced slowed reaction times as task difficulty increased. Thus, response times were fastest for the 1-target maintenance condition, next fastest for the 2-target maintenance condition, third fastest for the 1-target updating condition and slowest for the 2-target updating condition. For maintenance conditions, as anticipated, younger adults were faster than older adults who were in turn faster than stroke group participants. For updating conditions younger adults were again faster than older adults but older adults were no faster than stroke group participants. This latter result is perhaps surprising as, based on previous research on tasks such as the flanker task (Rinne et al., 2013), we might anticipate that stroke participants would be slower than healthy age matched controls. Unfortunately the current data do not provide any clear insight into why this may have occurred. Finally, the addition of a second target in updating conditions resulted in a greater increase in response times for all groups than did the addition of a second target in the maintenance conditions. However the increase in response time was greater for older adults and stroke group participants, who did not differ from each other, than it was for younger adults (see Appendix B). Overall, however, our results are consistent with an age related slowing in response times. Examination of error rates demonstrated this same pattern of results.

4.3 DISTRACTOR INTERFERENCE (DI) EFFECTS ON WORKING MEMORY

The critical analysis of this dissertation determined how the presence of distractors affected working memory performance as a function of working memory load. Distractor interference (DI) for both response time (RT) and error rate (ER) was calculated as:

$$\text{DI} = \text{condition (distractors present)} - \text{same condition (distractors absent)}$$

The hypotheses were four-fold. First, we hypothesized that overall, the presence of distractors would impact working memory performance through increased RT and ER regardless of group membership. Second, we hypothesized that the DI would be larger for updating conditions than for maintenance conditions because additional central executive resources would be recruited for the working memory task, thereby reducing the central executive resources available for selectively attending to task-relevant targets while also inhibiting processing of task-irrelevant distractors. Third, based on the inhibitory deficit hypothesis (Hasher & Zacks, 1988), we proposed that older adults would be more likely to have difficulties inhibiting processing task-irrelevant distractors, resulting in increased DI for older adults compared to younger adults. Finally, based on the results of studies such as those conducted by Rinne et al. (2013), we postulated that stroke group participants would be more affected by the presence of distractors than healthy older adults, owing to attention and working memory deficits often seen in stroke.

4.3.1 DI AS A FUNCTION OF AGING AND STROKE

As outlined above in the third and fourth hypotheses, we predicted increased DI with age and additional increases in DI as a function of stroke status. We also postulated that DI for older and stroke group participants would be more affected by increases to working memory load. However neither hypothesis was supported in Chapter 3. Both older adults and stroke group participants responded to the presence of distractors in the same fashion as younger adults (Appendix B analysis). Thus, the following discussion of the effect of distractors on working memory performance pertains equally to all three populations.

4.3.2 DI AS A FUNCTION OF WORKING MEMORY LOAD

Consistent with our first hypothesis, DI effects were present for both maintenance and updating conditions. However DI effects did not vary across working memory load conditions as we predicted. In general, DI effects were similar across maintenance conditions regardless of the number of targets. This was in line with our hypothesis that maintenance of target items requires minimal top-down central executive resources and should not induce greater distractor effects. However, contrary to our prediction of increased distractor interference with increased task difficulty the DI was *smaller* for the 2-target updating task than for any other condition.

We proposed that as task difficulty increased, participants might have applied more stringent attentional control (selective attention) to minimize the effects of the irrelevant distractors in order to better attend to the relevant material. That is, during the maintenance tasks, although central executive resources were available, they were not deployed because of the simplicity of the task. Even though the addition of a second target slowed participants and resulted in increased ER, the task was still performed quickly and with few errors. Given the continued ease of the task, additional top-down control mechanisms may not have been brought online. Furthermore, although the 1-target updating condition was more difficult than the 2-target maintenance task, as evidenced by increased overall RT when comparing these 2 conditions, DI effects were still generally equivalent. The 2-target updating task was the most difficult task, particularly for older adults and stroke group participants, but distractor interference diminished. Thus, once the task became more difficult, it is proposed that participants brought attention control resources online in order to facilitate performance.

4.3.3 DISTRACTOR INTERFERENCE (DI) BEYOND 2-TARGETS

The proposed theory was that the task demands needed to be sufficiently high before participants would engage attention control mechanisms. In Chapter 3 it was apparent that the task became substantially more difficult for older adults and stroke participants compared to younger adults seen in Chapter 2, as evidenced by the greater increases in response times an error rates relative to all other conditions at the 2-target updating level. However, in the case of younger adults it was less clear whether participants encountered significant challenge, even for the 2-target updating task. A second experiment tested whether younger participants would still be able to filter task irrelevant distractors under even higher levels of working memory load (i.e., requiring them to either maintain or update 3 or 4 targets). That is, at the 2-target updating level it appears the task was sufficiently difficult *and* participants still had resources that could be devoted to filtering task-irrelevant information. We hypothesized an inflection point after which increased working memory load would deplete executive resources to the point where participants' filtering ability would be compromised.

DI was similar across maintenance conditions regardless of the number of targets further supporting the theory that simply increasing the number of maintained targets recruited minimal executive control resources. The hypothesized inflection point was also supported by the data, which showed that increasing the number of targets for the updating task from 2 to 3 resulted in increased distractor interference for both response time and error rate. The interpretation of these data was that up until the 3-target updating condition sufficient central executive resources were available for the central working memory task and selective attention. Increased DI for the 3-target updating condition compared to the 2-target updating condition suggest that central executive resources were largely consumed by the working memory task and that fewer resources could be put towards selective attention processes. However, this interpretation became muddied by the 4-target updating condition data, for which there was no DI.

It is possible that participants employed a different strategy for the 4-back condition than for any of the other conditions. The n-back task is a recognition task, as opposed to a recollection task, that can be completed successfully using either familiarity based or recollection based processes (Juvina & Taatgen, 2007; Kane et al., 2007). Participants had to update an increasingly large sequence of letters but they still only had

3 seconds to respond on each trial. Using a recollection-based process such as verbal rehearsal may have become too unwieldy and forced participants to rely on a familiarity-based process.

The theory that selection strategy can affect the influence of distractors on task performance has been investigated in the visual search literature. For example, Leber and Egeth (Egeth et al., 2010; Leber & Egeth, 2006) have proposed that the individuals can employ one of two search strategies: a) singleton search mode in which the "odd-item-out", i.e., therefore the most salient item, is assigned the highest selection priority or b) feature search mode in which the individual assigns a certain feature as the highest selection priority. They found that when participants employed a feature search mode their visual search performance were unaffected by distractors that did not match the feature search mode template held in mind. In a similar vein, Juvina and Taatgen (2007) proposed two different strategies for completing the n-back task: high-control and low-control. The high-control strategy involves rehearsal whereas the low-control strategy employs a familiarity or recency judgment. Given the time constraints placed on each trial it seems feasible that participants were forced into using a low-control strategy. It could be the case that the high-control strategy is more sensitive to distractors and more sensitive to changes in working memory load. However, we did not specifically control for strategy use, and although anecdotally participants reported having to do things "differently" for the 4-target task, no systematic inquiry was made into how participants adapted to the increased working memory load. This suggestion needs to be tested empirically.

4.3.4 INTERIM CONCLUSION

Notwithstanding the results of the 4-target updating task, in general the data support the theory when a task is of sufficient difficulty *and* sufficient executive control resources remain, the individual will employ additional attention control processes to facilitate task performance.

4.4 FOCUSSING OF THE ATTENTIONAL WINDOW: AN EARLY ATTENTIONAL CONTROL PROCESS TO FACILITATE WORKING MEMORY PERFORMANCE UNDER DIFFICULT CONDITIONS

In Chapter 2 and 3 of this dissertation we have argued that, for relatively simple working memory tasks, individuals do not necessarily engage attention control mechanisms to limit inputs to working memory. Once the central working memory task becomes more difficult, individuals apply an attentional control mechanism to deal with task-irrelevant information. We have also argued, based on the analysis of distractor interference across the response time distribution in Chapter 2 and 3, that this attentional control mechanism is implemented early in the information processing time course rather than late. However, the dichotomous view of all or nothing application of attention control may be overly simplistic. Whether the task is simple or complex, visual attention must be deployed such that the individual can attend to the relevant material to make accurate task-relevant judgments. Thus, attention must always be controlled in some fashion for goal directed action. So, how can the current study contribute to our understanding of how visual attention is deployed to facilitate performance on an increasingly difficult memory task?

Throughout this dissertation we have alluded to one of the most prominent theories of human visual attentional control, “the attentional window” (e.g., Theeuwes, 2010), i.e., we control the flow information entering into working memory by placing constraints on how much of the visual scene we attend to. Numerous studies have demonstrated that individuals can change the size of the attentional window to be broad or narrow (Belopolsky & Theeuwes, 2010; Belopolsky et al., 2007; Theeuwes, Belopolsky, & Olivers, 2009; Van der Stigchel et al., 2009). For example, Belopolsky et al. (2011) presented participants with a central RSVP stream surrounded by 8 shapes (7 identical, and 1 singleton). Participants completed a visual search task for a singleton shape in which they used either a diffuse or focused attentional window. In the diffuse attentional window condition participants could only initiate the search for the singleton shape once the global shape of the stimuli was a circle. In the focused condition, participants only began the search once they saw the letter K in the central RSVP stream. In both conditions, participants also encounter trials in which one of the 8 shapes was a colour singleton distractor. Their results showed that participants’ response times were not affected by the presence of distractors when they employed a focused attentional window but they were slowed by the presence of distractors when they employed a diffuse attentional window. Overall, these data suggest that when the attentional window is broadened, exogenous distractors, such as colour singletons, easily capture attention and slow response times on the central discrimination task. In contrast, when the attentional window is narrowed, exogenous distractors do not appear to influence visual search performance.

Another important aspect of the attentional window theory of attentional control is it's time-course (Heitz & Engle, 2007). Heitz and Engle have argued that it takes time for the individual to apply a spatial constraint, i.e., to narrow the focus of the attentional window. In their 2007 study, Heitz and Engle had participants complete a flanker task with differing time constraints across blocks of trials, ranging from 200-700 ms. Accuracy was assessed across the response time domain, and the authors found that while participants accuracy for incompatible flanker trials began to improve after 300 ms, they reached a 'peak level' of accuracy after approximately 400-500 ms. The authors interpreted this to mean that the gradual increase in accuracy was a reflection of the gradual decrease in the size of the attentional window.

The data presented here are in line with the attentional window theory of visual selective attention and with Heitz and Engle's proposal that it takes time to narrow the focus of attention. For instance, during the maintenance tasks, the distractor interference effect was consistent, or increased, across the response time distribution, suggesting that the attentional window was broad and that there was no attempt to "focus attention" even as the number of to-be-remembered items increased from 1 to 2. In contrast, during the updating tasks, distractor interference was consistent, or increased, across the response time distribution for the 1-target updating task, but showed a negative slope across the response time distribution for the 2-target updating task. This latter result suggests participants were focusing the attentional window to gradually eliminate the distractor interference effect.

One prominent alternative view is the idea of search modes, first discussed in the previous section (Egeth et al., 2010; Lamy, Carmel, Egeth, & Leber, 2006; Leber &

Egeth, 2006). In the previous section we postulated that the search strategy might be a relevant factor in determining the extent to which distractors influence performance, and indeed Leber and Egeth have suggested that feature search mode (specific target features) is less susceptible to distractors than is a singleton search mode (e.g., odd-man out). Applying Leber and Egeth's search mode theory to the current data in which distractor interference decreased with increased working memory load leads to the possible alternative conclusion that participant use a singleton search mode for simpler tasks (i.e., maintenance tasks and the 1-target updating task) but engage a feature search mode when the working memory load is increased. This conclusion, while possible, is unsatisfying for two reasons. First, it is not clear why the change in working memory load would precipitate a change in search mode strategy. The central target's distinguishing feature, i.e., it is the only upright letter, is more inline with feature search mode (inverted vs. upright letter) criteria rather than singleton search mode criteria (i.e., physically distinguishing features that increase salience such as colour or shape). Thus, it seems more likely that that the same feature-search mode would be employed across conditions. It then becomes more difficult to explain the difference in distractor interference across conditions. Another difficulty in determining whether search modes theory offers a better account of our current data is that there is no information regarding the time-course of search modes (i.e., do different search modes take different amounts of time to implement?). Thus we cannot compare our current data with search mode theories across the response time distribution, which we were able to do with the attentional window account. However, search mode theory does suppose parallel processing of all visual information (Awh, Belopolsky, & Theeuwes, 2012). Thus, we can extrapolate that the attentional control mechanisms brought to bear in search mode theory would have to occur later in the time course (i.e., post-perceptual). As previously discussed, our current data suggest that the attentional control mechanism is being engaged very early in processing, casting further doubt on the possibility that participants engaged a search mode to limit the effects of distractors on performance of the working memory tasks.

Overall these data support the attentional window theory of visual attention control. Furthermore, these data suggest that when task demands are simple the default distribution of visual attention is broad. However, when the working memory task demands become more difficult, participants focus the attentional window in order to limit the effect of task-irrelevant distractors and support working memory performance.

4.5 PRESERVATION OF ATTENTION CONTROL IN AGING AND STROKE

4.5.1 PRESERVATION OF ATTENTION CONTROL IN AGING

The current data suggest that at least in some instances attention control is preserved in aging. As previously discussed in Chapter 3, the current findings do have some support (e.g., Gazzaley et al., 2008; Ishigami & Klein, 2011; Quigley, Andersen, & Müller, 2012). Notably, as in Ishigami and Klein (2011) the task we employed produced distractor interference effects by presenting flanking distractors that were spatially separated from the target. Ishigami and Klein showed that older adults were slower but responded more accurately on the Attention Network Test (ANT). They proposed that age did not interact with orienting or executive networks but the two groups had different foci: younger adults were biased towards speed while older adults were biased towards accuracy. Quigley et al. (2012), had younger and older adults complete a task in which they had to monitor a centrally presented RSVP stream consisting of overlapping small and large letters. Participants had to detect and respond to a predetermined target in one stream (i.e., small or large letters) while ignoring the other. The authors found that the detection ability of older adults was as good as the detection ability of younger adults. Older adults appeared to be able to employ spatial attention control in a manner similar to younger adults. Thus, in the current experiments it appears that the sample of older adults was as proficient as younger adults at inhibiting processing of concurrently presented distractors through the use of controlled spatial attention.

Studies by Gazzaley et al. (Gazzaley, Cooney, Rissman, et al., 2005; Gazzaley et al., 2008) do suggest that older adults may have more difficulty with distractors presented during the maintenance phase. Thus, older adults may have more difficulty protecting the contents of working memory during the maintenance period rather than at encoding (i.e., when distractors are presented simultaneously with targets). However, the current data cannot address the theory.

4.5.2 PRESERVATION OF ATTENTION CONTROL IN STROKE

The current data also showed some preservation of attention control, at least with respect to the n-back task, for stroke group participants. This result seems particularly surprising given the prominence of post-stroke attention and working memory difficulties (e.g., McDowd, Filion, Pohl, Richards, & Stiers, 2003; Stapleton, Ashburn, & Stack, 2001). However, Rinne et al. (2013) found that although stroke group participants were slower and less accurate than controls on the ANT, stroke status did not interact with cue or flanker variables on measures of response time or error rate (though see their results for separable effects of lesion location). Moreover, these participants were tested in the acute phase of stroke recovery, i.e., < 2 months post-stroke, the period in which attention related deficits are thought to be most severe (Barker-Collo, Feigin, Lawes, Parag, & Senior, 2010; Robertson et al., 1997). Stroke group participants in the current study were highly educated, highly motivated individuals well into the post-acute phase of recovery (i.e., an average of 5 years post stroke). In addition, because this study examined effects of stroke in general, we did not select for stroke severity or location. Thus, retrospectively it may not be surprising that our stroke group performed similarly to our healthy older adults.

We predicted that because of the large overlap between working memory and attention processes (Awh et al., 2006) increased strain on working memory resources would result in compromised ability to selectively attend to task-relevant information while ignoring task-irrelevant distractors, particularly for stroke survivors – a group characterized by attention and working memory difficulties. However, we found no evidence for the predicted increase in distractor interference effects.

4.6 LIMITATIONS AND FUTURE DIRECTIONS

There are several limitations in the current study. Although the use of the n-back task facilitated the independent manipulation of two different aspects of working memory, i.e., the central executive and the phonological loop there are some task limitations as it was implemented here. First, in distractor conditions the distractors were present both at encoding and at response. As a result it is currently unclear at what stage of processing distractor interference occurred. Efficient filtering at the encoding phase would not be predicted based on Hasher and Zacks theory of cognitive aging (Hasher & Zacks, 1988). Future studies in which distractors are present at encoding or at response time but not both and could be accomplished by using versions of the n-back task employed in this dissertation that do not require a response to every stimulus but make periodic demands of the participant to determine whether the current stimulus is the same as the target stimulus seen ‘n’ trials previously.that manipulate timing of distractor presentation may be particularly pertinent in the study of healthy older controls and stroke participants to determine if individuals were filtering distractors at the encoding stage versus resolving the response conflict at post-perceptual stages. Second, the current experiment only loaded the phonological loop but did not apply any independent load on the visuospatial sketchpad. Thus it is possible that distractor processing / inhibition may be, in part done by the visuospatial sketchpad rather than the central executive alone. It is also possible that the lack of distractor interference effects for the 4-back updating task were a result of switching to non-verbal recollection processes rather than familiarity processes, and the current data set is not well suited to distinguishing which may be true.

We chose to use inverted or rotated letters as “task-irrelevant” distractors in an effort to maintain equivalent target-distractor stimulus complexity. However, the current data along with an additional experiment in our laboratory (Weisskopp, Wilson, & Eskes, unpublished) suggest that these distractors may have been processed in the same manner as upright letters. That is, they were “read” in the same fashion as the targets. The result is that our distractor condition was the equivalent of incongruent target-distractor pairings similar to those found in the classic Ericksen and Ericksen paradigm. Replication of this experiment with upright, congruent, incongruent, and neutral target-distractor pairings along with the distractor absent conditions may make comparison easier between the current experiment and others that employ flanker tasks. In addition, manipulations of target and distractor types (i.e., different target/distractor combinations of letters and simple shapes) may also help tease out whether non-verbal processes were employed in the current paradigm.

There are additional limitations regarding our recruitment of participants. Our stroke group participants were highly motivated, well educated individuals and may not be a representative sample of stroke survivors in the general public, thus limiting generalizability of the current results. Although our healthy control and stroke group participants were well matched on age and education there were significantly more men in the stroke group than in the control group. Sex differences have been reported in cognitive functioning with women showing an advantage for perceptual speed and verbal and memory tasks while men show an advantage for spatial tasks (e.g., Maitland, Intrieri, Schaie, & Willis, 2000). However, as noted by Maitland et al., the perceptual speed advantage for women diminishes with age. In the current experiments it would seem most likely that these cognitive advantages should result in a greater advantage for the control group, given there were more women in this group. However, overall group differences for both response time and error rates were minimal and were not evident for distractor processing, suggesting sex differences played a minimal role in the current results.

Finally, although the task clearly became more difficult, it could be the case that 2-target updating condition was still not difficult enough to deplete working memory resources to the point where selective attention processes became compromised. Follow-up with a study similar to Chapter 2: Experiment 2 would further extend our current findings.

4.7 CONCLUSION

Despite its limitations, the data in this dissertation allow for a number of postulations about how working memory and attentional control interact. First, when a working memory task is easy, attentional control mechanisms are either not at all or minimally engaged. As the task becomes more difficult, attention control mechanisms are brought online to minimize the impact of task-irrelevant distractors, likely in the form of an “attentional window” that constrains the processing of information to a small area of the visual space. As with tasks such as visual search, the current data suggest that the magnitude of the distractor interference effect is not only task dependent, but also strategy dependent. Second, there appears to be a task-strategy interaction such that too easy a task results in minimal use of selective attention process, optimal task difficulty results in allocation of central executive resources to both the central task and to more stringent application of attention control processes, and that more difficult tasks result in central executive resources being prioritized for the central working memory task and application of the more stringent selective attention processes is no longer possible. Third, these data also suggest that healthy older adults and stroke survivors are able to apply more stringent top down attentional control filters to protect the contents of working memory from intrusions by task-irrelevant stimuli presented at the encoding phase, in a similar fashion to healthy young adults. Substantial research efforts aimed at cognitive rehabilitation (for recent reviews see Cicerone et al., 2011; Melby-Lervåg & Hulme, 2013; Poulin, Korner-Bitensky, Dawson, & Bherer, 2012) have in part led to the emergence of commercial attention and working memory training products such as Lumosity and Cogmed. In this landscape it is therefore imperative to continue to examine which aspects of attention and working memory are affected by stroke and how these mechanisms interact in order to produce targeted, effective interventions.

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APPENDIX A: SUPPLEMENTARY DATA ANALYSIS FOR CHAPTER 2

Table A1

Comparison between mixed effects models and typical analysis of variance (ANOVA)

	Response time						Error rate				
	bits		F	*p*		ges	bits		F	*p*	ges
distractors	612.0	*	210.8	0.000	*	0.090	2.4		2.3	0.143	0.016
# targets	1359.0	*	40.2	0.000	*	0.147	20.5	*	6.5	0.020	0.060
task	2014.3	*	49.1	0.000	*	0.211	-0.3		0.8	0.397	0.005
distractors × # targets	-0.7		0.3	0.607		0.000	-2.9		0.1	0.718	0.001
distractors × task	32.3	*	3.3	0.085		0.004	-1.0		2.4	0.142	0.005
# targets × task	441.5	*	20.3	0.000	*	0.056	-2.4		0.4	0.525	0.002
distractors × # targets × task	30.1	*	8.0	0.011	*	0.004	-2.9		0.0	0.989	0.000

*Note. bits = Bits of evidence (log-base-2-AIC-corrected likelihood ratios), AIC = Akaike information criterion, ges = Generalized eta squared. * indicates bits > 3.00 or p* < .05

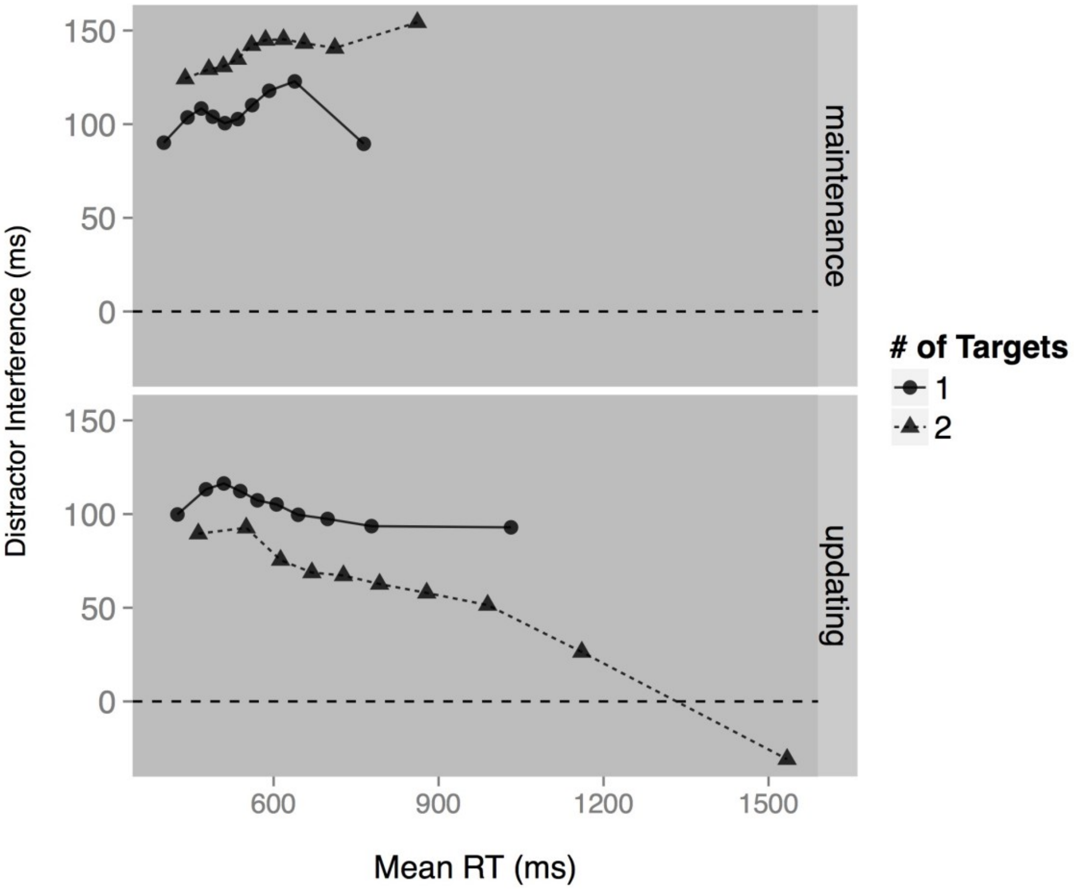

Figure A1 Delta plots examining distractor interference (DI) across the complete RT distribution by condition. RTs for each condition were ordered fastest to slowest and then binned into deciles. Distractor interference and mean RT was computed for each bin and DI is plotted as a function of RT. The longer RTs in the 2-target updating condition showed a smaller DI. However, even at comparable RTs (between 500 – 1000 ms) the DI is still smaller in the 2-back condition than in the other conditions, suggesting different or additional processes are engaged for the more difficult task.

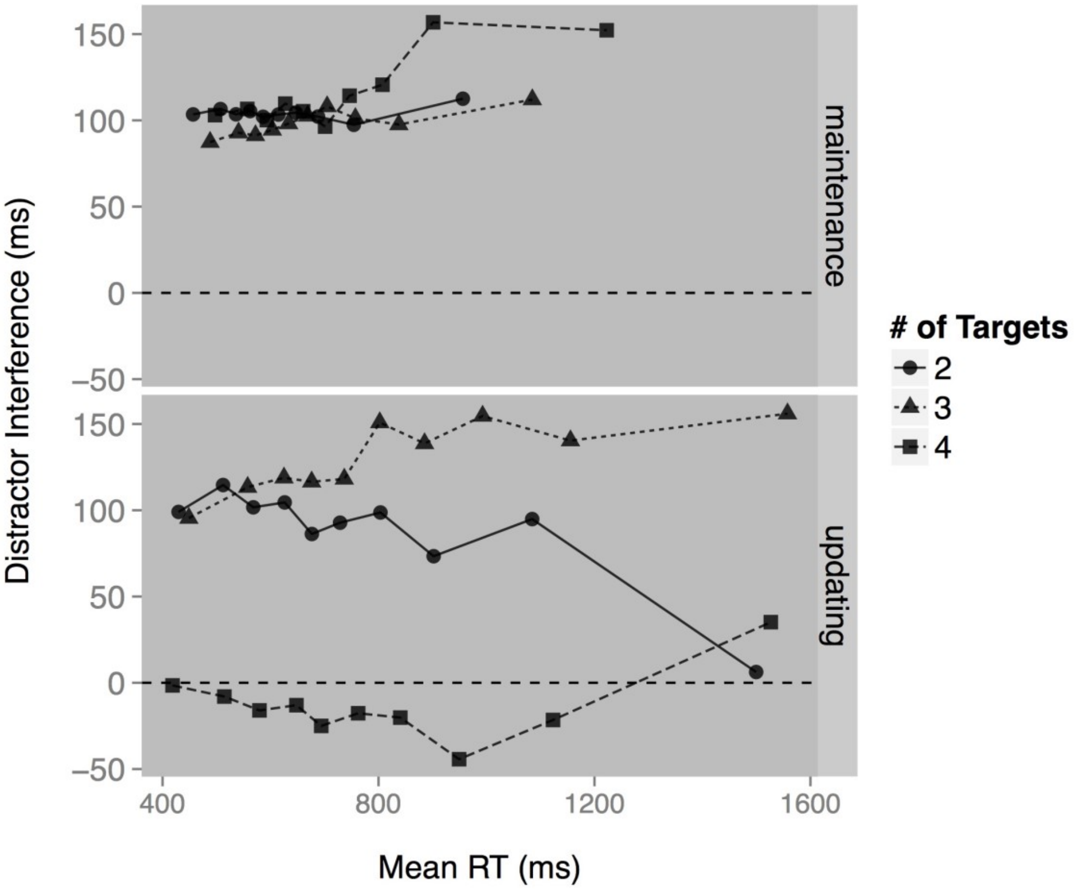

Figure A2 Delta plots examining distractor interference (DI) across the complete RT distribution by condition for Experiment 2. RTs for each condition were ordered fastest to slowest and then binned into quintiles. Distractor interference and mean RT was computed for each bin and DI is plotted as a function of RT. Maintenance tasks showed flat or positive slopes. Both the 2-target and 4-target updating conditions showed some evidence of decreasing DI with increasing RT. At longer RTs the DI for 2-target updating task becomes smaller than the 3-target updating task. In the 4-target updating condition, the longest RTs produced the largest DE, and over the mid-range RTs, there appeared to be a speed advantage in the presence of distractors.

APPENDIX B: SUPPLEMENTAL ANALYSIS FOR CHAPTER 3

The Statistical analytic section was placed in supplemental material for Chapter 3 to facilitate submission of the manuscript to Journal of Gerontology: Series B Psychological Sciences. Note that the analysis outlined here is identical to the methods employed in Chapter 2.

STATISTICAL ANALYSIS

Generalized Linear Mixed Models (GLMMs; Pinheiro & Bates, 2000) were employed to analyze the response time (RT) and error rate (ER) data, using distractors (absent vs. present), targets (1 vs. 2), and task (maintenance vs. updating) as effects of interest. Mixed effects modeling was chosen as the primary analytic tool as it offers multiple benefits over the typical analysis of variance (ANOVA). Please see Lawrence and Klein's recent work for a review of the benefits of treating response time and error rate data using mixed effects (Lawrence & Klein, 2012). Wilson and Eskes (submitted) also found comparable results whether using mixed effects models or ANOVA when analyzing a data set using this identical task in a sample of healthy young adults.

Briefly, to ascertain whether an effect of interest explains a significant portion of the variance in the data collected, GLMMs are computed and compared. For example, to determine whether the independent variable 'task' explained a significant amount of variance in the data collected for this experiment, two models were computed and compared using likelihood ratios: an unrestricted model composed of the Grand Mean, participant means, and the effect of task, vs. a restricted model composed of the Grand Mean and participant means only (Glover & Dixon, 2004; Johansson, 2011). The likelihood ratio describes the relative likelihood of one model compared to the other. For example, in the current data set, what is the likelihood that a model that includes the effect of task does a better job of explaining the variance in the data when compared to the model that does not include the effect of task?

To control for family wise error rates an arithmetic correction was applied – Akaike's Information Criterion (AIC; see Fang, 2011; Stone, 1977). For ease of interpretation the final AIC-corrected likelihood ratios are presented as "bits of evidence" using the log-base-2 scale. The sign of the reported bits of evidence represents whether the data support the unrestricted model (+) or the restricted model (-). The magnitude of the reported bits of evidence represents the strength of the evidence for a given model. In the current experiments all model comparisons are reported so that the reader can make their own interpretation regarding the data. We used a qualitative cut-off of 3.00 bits of evidence (equivalent to a likelihood ratio of 8) as a threshold for determining whether we deemed an effect significant or not. This was based on thresholds proposed by Royall (1997), namely that a likelihood ratio of 8 reflects "pretty strong" evidence in favour of one model over another while a likelihood ratio of 32 (equal to 5 bits on the log-base-2 scale) reflects "strong" evidence for one model over the other.

In order to complete post-hoc comparisons between the various conditions, point estimates were obtained from the corresponding model and confidence intervals were generated using a posteriori bootstrapping methods[5]. To generate the confidence intervals, the model's estimate of the grand mean, and its covariance with other effects,

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[5] Readers will note that the use of point estimates (PE) and confidence intervals (CI) generally makes reporting an effect size somewhat redundant from the point of view that effect sizes are generally meant as a measure of the signal-to-noise ratio and confidence intervals provide the same information, albeit in a slightly different presentation. Those interested in an effect size like measures might find an equation such as 2*PE/CI a useful estimator for the effects reported here.

was zeroed. This results in confidence intervals for each condition that estimate intra-subject variability (how performance varies for all participants for each condition) without confounding it with inter-subject variability (how average performance varies from subject to subject within each condition), and allows for the comparison of conditions (c.f. Masson & Loftus, 2003).

Analysis and visualization was coded in R (R Development Core Team, 2013) using the lme4 package (Bates, Maechler, & Bolker, 2011) for computing GLMMs and the ggplot2 package (Wickham, 2009, 2012) for visualizations. Convenient wrapper functions for these computations and visualizations are provided by the 'ez' package (https://github.com/mike-lawrence/ez), developed by Mike Lawrence.

Table B1

Response times and error rate analysis comparing healthy younger, healthy older, and stroke group participants.

	Response Times	Error Rates
distractors	1205.05	-2.35
group	35.72	13.97
targets	4620.47	526.99
task	6420.51	422.71
distractors × group	-1.59	2.32
distractors × targets	12.91	-2.56
distractors × task	100.14	-1.81
group × targets	278.86	89.93
group × task	350.00	164.07
load × task	2392.18	128.06
distractors × group × targets	-2.22	-4.68
distractors × group × task	-1.88	-4.76
distractors × load × task	65.95*	-2.11
group × load × task	333.47*	50.76*
distractors × group × load × task	-0.45	-5.34

Note Results are in Log-Base-2-AIC-Corrected Likelihood Ratios and presented as ‘bits of evidence’. AIC = Akaike information criterion. * indicates highest order significant model

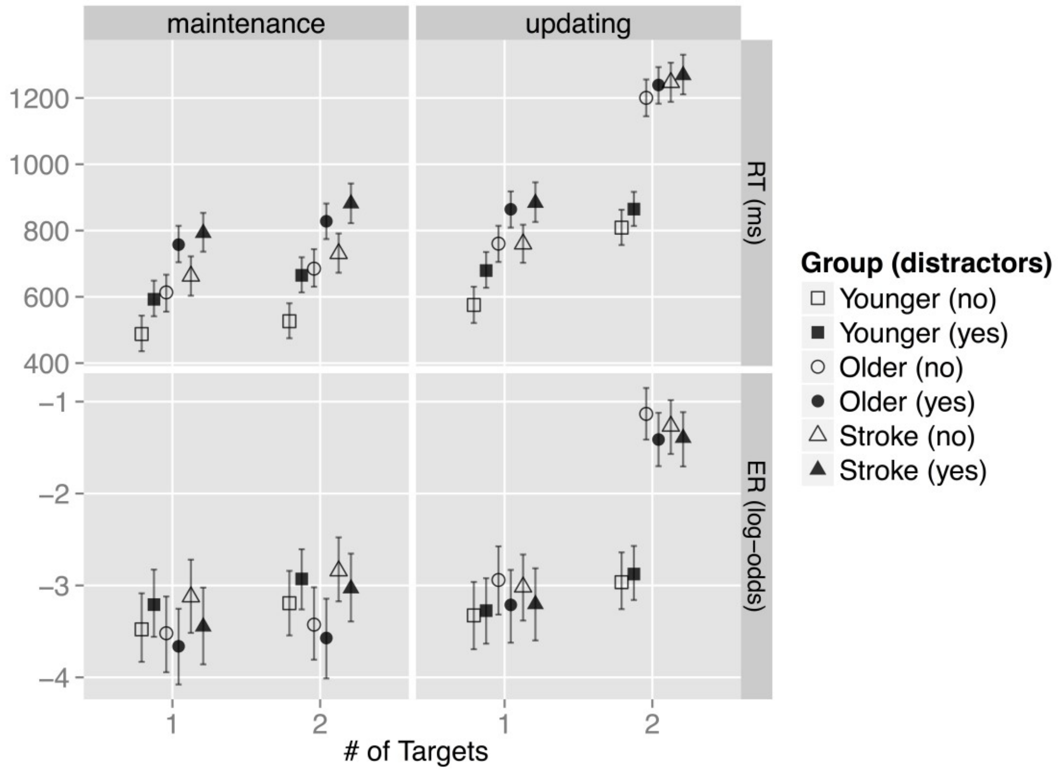

Figure B1 Visualization of response time and error rate data for healthy young, healthy older and stroke group participants. Error bars represent 95% CI for each point estimate as detailed in the Statistical Analysis section

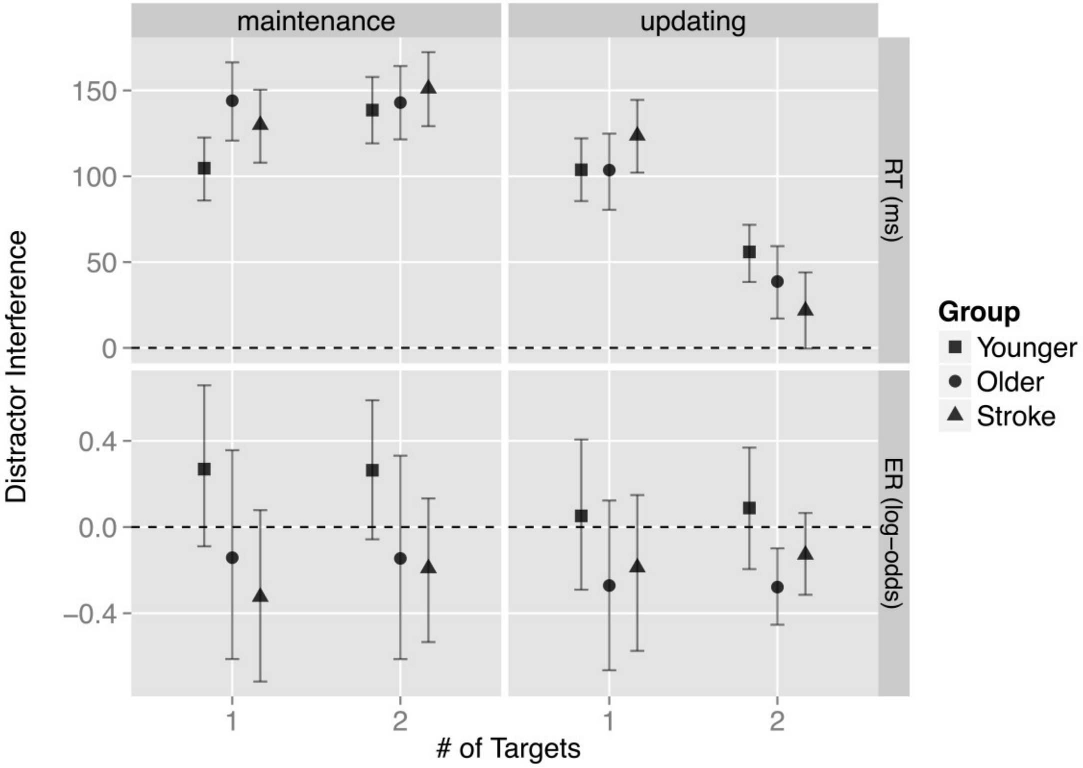

Figure B2 Distractor Interference effects across conditions for healthy younger, healthy older, and stroke group participants. Distractor Interference (DI) was calculated as condition with distractors minus same condition without distractors. If the error bars do not cross 0 (dashed line), it is considered a significant DI for that condition.

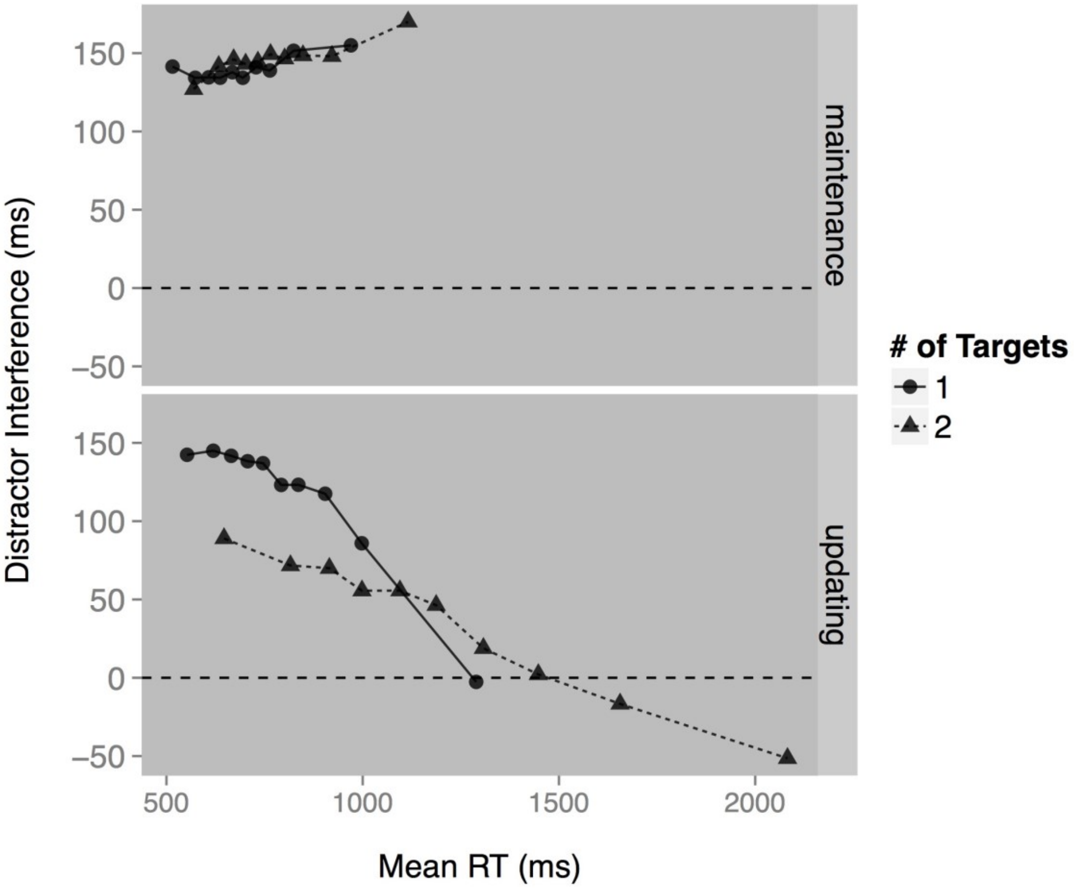

Figure B3 Delta plots examining distractor interference (DI) across the complete RT distribution by condition. RTs for each condition were ordered fastest to slowest and then binned into quintiles. Distractor interference and mean RT was computed for each bin and DI is plotted as a function of RT. Maintenance tasks showed flat or positive slopes. Both the 1-target and 2-target updating conditions showed some evidence of decreasing DI with increasing RT. Even at similar RTs, DI was smaller for the 2-target updating condition than the 1-target updating condition, for most of the RT distribution.