Interference Control in Memory and Fluid Intelligence

by

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Abstract

This thesis investigated the role of interference in general cognitive functioning. Study 1 explored the relationships among interference control, memory, and fluid intelligence. Studies 2 and 3 explored the possibility that interference is controlled by suppressing the interfering information rather than, for example, facilitating the target information.

Study 1 tested the hypothesis that individual differences in the ability to regulate interference are responsible for the correlation between memory tasks and fluid intelligence. Participants completed common measures of working memory, long-term memory, fluid intelligence, and interference regulation. In structural equation models, controlling for interference regulation ability largely accounted for the correlation between the memory tasks and fluid intelligence. These results suggest that efficient interference control is critical to cognitive functioning.

Study 2a tested the hypothesis that interference is regulated by suppressing competing responses. In Phase 1 of a three-phase paradigm, participants performed a vowel-counting task that included pairs of orthographically similar words (e.g., allergy/analogy). In Phase 2
participants solved word fragments (e.g., a _ l _ _ gy) that resembled both words in an earlier pair, but could be completed only by one of these words. Phase 3 measured the consequence of having resolved interference in Phase 2 by asking participants to read a list of words, including the rejected competitors, as quickly as possible. Relative to participants in control conditions that did not require interference resolution these interference condition participants were slower to name competitor words. Study 2b showed that while competitors are suppressed during interference resolution, a complementary facilitative process does not directly enhance accessibility of targets.

Finally, Study 3 tested the hypothesis that older adults have impaired suppression abilities. Older adults were tested in the same paradigm used in Studies 2a and 2b. In contrast to younger adults, older adults showed no suppression of competitors. This result supports the theory that some age related memory deficits stem from impaired suppression processes.
Acknowledgments

Being a good scientist requires at least three core qualities: first, an abiding curiosity, a hunger for answers; second, a deep knowledge of your chosen field so you can pick the most interesting and important questions; and finally, the skill to design incisive experiments that give clear answers to your questions. To the extent that I have any of these qualities it is thanks to a handful of special people. For my curiosity I thank my parents, Keith and Charlotte, not just for good genetics but also for always nurturing my inquisitiveness and letting me choose my own path. For my knowledge and skill I thank my advisor, Lynn Hasher, who is one of the most creative and clever experimentalists in the field and has a depth of knowledge I can only aspire to. For being the glue that holds it all together and for supporting me in uncountable ways, I thank my wife Krista.

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Chapter 1 Introduction

Human cognition is limited; on almost any cognitive task there is an upper limit on performance. For example, students experience limits on how much information they can remember, no matter how hard they study, scientists encounter problems too difficult to solve no matter how hard they think. Psychologists have long been interested in understanding the source and nature of these limits. Perhaps the clearest and most influential example of this tradition is George Miller’s famous “magical number seven” (1956)—a proposed limit on the number of units that can be stored in short-term memory. While the details continue to be debated (see Cowan, 2000 for an extensive review), the notion that there is a fundamental limit on the amount of information that can be recalled after a short delay remains a staple of short-term and working memory theories. Some propose that there is a focus of attention that is limited in the number of items it can hold (Cowan, 2000, 2010; Oberauer, 2002), others that time based decay of information in working memory limits storage (e.g., Baddeley, Thomson, & Buchanan, 1975; Towse, Hitch, & Hutton, 1998), and others that the ability to form and break arbitrary bindings is critical (Oberauer, 2005). Still others suggest that working memory (Kane, Conway, Hambrick, & Engle, 2007) is limited by the ability to control the allocation of attentional resources (for

1 There is a long and ongoing debate about whether there are distinct cognitive and neural systems that correspond to the labels short-term and working memory (see Jonides et al., 2008 for a recent review). However, the overlap between the two terms is sufficient to allow them to be used interchangeably in the present context.
additional views see chapters in Conway, Jarrold, Kane, Miyake, & Towse, 2007). All of the views share the notion that some aspect or aspects of the cognitive system places an upper limit on successful recall.

The research reported here tests the theory that memory retrieval as well as other aspects of cognition are limited by the efficiency of attentional mechanisms that control various sources of interference (Hasher, Lustig, & Zacks, 2007; Hasher, Zacks, & May, 1999; Healey, Campbell, Hasher, & Ossher, 2010). To this end, the thesis has three major sections. In the first section I explore how limited short-term retrieval impacts other aspects of cognition such as reasoning, and test the theory that a major limiting factor in memory retrieval is the ability to control interference. In the second section I explore the nature of interference control mechanisms. Interference may be controlled by facilitating, or up-regulating, target information; alternatively it may be controlled by suppressing, or down-regulating, competition information, or by a combination of facilitation and suppression. I test these various possibilities in the second section. In the third section I explore age differences in interference control through suppression, testing the hypothesis that relative to younger adults, older adults have impaired inhibitory processes, at least partially accounting for their generally poorer memory retrieval (Zacks & Hasher, 2006).

Consequences of memory limitations

One of the key findings of the last several decades of working memory research is that the extent of the memory limit varies among individuals and that the individual differences correlate with a wide range of other cognitive abilities, such as reading comprehension, problem solving, and reasoning (e.g., Daneman & Carpenter, 1980; Conway et al., 2005; De Beni, Borella, & Carretti, 2007; Kyllonen, 1996; Daneman & Merikle, 1996). The diversity of
cognitive abilities predicted by working memory tasks has lead some to suggest that the same mechanisms that limit working memory underlie individual differences in fluid intelligence, a theoretical, domain-general thinking and reasoning ability critical for complex cognition (e.g., Kane et al., 2007; Healey, Zacks, Hasher, & Helder, submitted).

The concept of fluid intelligence originates from the observation that across a wide variety of tasks, an individual’s performance on one task tends to be positively correlated with performance on other tasks (Carroll, 1993). This so-called ‘positive manifold’ lead to Spearman’s notion of ‘general intelligence’: the idea that a general factor contributes to almost all cognitive tasks thereby producing the positive correlations between diverse tasks. General intelligence is usually measured with standard IQ tests such as the Wechsler Adult Intelligence Scale. General intelligence tests can be decomposed into two subcomponents: crystallized intelligence tasks which depend on acquired knowledge (e.g., vocabulary) and fluid intelligence tasks (e.g., tasks that require detecting and completing complex patterns), which are thought to measure a knowledge-independent aspect of general intelligence. Tasks designed to measure fluid intelligence tend to correlate quite highly with full scale IQ and can be administered in considerably less time than full IQ tests, leading to their popularity in individual differences research (Ackerman, Beier, & Boyle, 2005). Fluid intelligence tasks are psychometrically validated, widely employed in the literature, and have been used in an atheoretical manner as measures of a domain general cognitive ability without making a priori commitments as to what that ability may be (e.g., Friedman et al., 2006).

The strong correlations between working memory measures and fluid intelligence tasks ($r = .48$ according to a recent meta-analysis; Ackerman et al., 2005) have helped make working memory a central construct in the behavioral, neurocognitive, and neuropsychological literatures
on cognition (e.g., Miyake & Shah, 1999; Cowan, 2005; Conway et al., 2007), and have driven an explosion of interest in working memory within other sub-disciplines of psychology such as cognitive neuroscience, developmental psychology, clinical psychology, and educational psychology (e.g., Jonides & Nee, 2006; Awh, Vogel, & Oh, 2006; Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005; Shelton, Elliott, Hill, Calamia, & Gouvier, 2009; Kleider & Parrott, 2009; Hoffman, 2010) and in other fields, such as anthropology (Beaman, 2007; Coolidge & Wynn, 2007; Martin-Loeches, 2006; Wynn & Coolidge, 2006). Despite this prominent position there is still little consensus on exactly why working memory predicts fluid intelligence (e.g., Ackerman et al., 2005; Kane et al., 2007; Oberauer, Süß, Wilhelm, & Sander, 2007; Unsworth & Engle, 2007).

To understand the connection between working memory and fluid intelligence it is important to discuss how working memory is measured. Early researchers measured working memory (often called short-term memory) using simple span tasks. Simple span tasks present a short list of to-be-remembered items for immediate serial recall. For example, word span presents words for recall. However, much of the work supporting the connection between working memory and fluid intelligence has used complex span tasks, rather than simple span tasks to measure working memory limits. Complex span tasks present a series of to-be-remembered items interleaved with some processing task (e.g., operation span alternates between presenting to-be-remembered words and simple math equations, which the participant must solve). Complex span tasks have their roots in the early working memory literature in which working memory was conceived to be a temporary storage system, distinct from the long-term memory system, that holds information in a highly accessible state so it can be used in ongoing cognitive processing (Baddeley & Hitch, 1974; See Baddeley, 2003 and Miyake & Shah, 1999 for recent conceptions). Such a view of working memory predicts that individuals with a larger
working memory capacity (i.e., those who can store more information in an accessible state) should outperform individuals with a smaller working memory capacity on any task that places demands on working memory. However, the predicted correlations were not found using existing measures of short-term memory such as simple span tasks (e.g., word span), which requires immediate serial recall of a short list of items (e.g., nouns). Daneman & Carpenter (1980) suggested that simple span tasks failed to predict other cognitive abilities because the tasks require very little manipulation of the to-be-stored information, whereas working memory is a system for storing and manipulating information. Complex span tasks were designed to better capture the interplay between storage and processing by taking a simple span task and interleaving a processing task (e.g., solving equations) between presentation of to-be-remembered items (Daneman & Carpenter, 1980; Turner & Engle, 1989). The number of items participants could recall in these tasks was viewed as a measure of the ability to hold information in an accessible state (i.e., the 'active maintenance assumption'; see Healey & Miyake, 2009) while processing other information.

The active maintenance assumption has run into difficulties in the face of evidence that the capacity for active maintenance is limited to at most five items (Cowan, 2000; 2010) and perhaps to as little as a single item (Oberauer, 2002). If we take operation span as an example, it is difficult to see how such a severely limited maintenance system could fully support recall of the 5 to 7 items as presented on the most difficult trials while also storing the intermediate products needed to solve the 5 to 7 associated equations. Such considerations have led many researchers to question the active maintenance assumption and to suggest instead that complex span tasks require retrieving information from long-term memory (Healey & Miyake, 2009; Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth & Engle, 2006; Unsworth & Engle, 2007). Long-term memory is theoretically distinct from traditional conceptions of working memory in
that the former involves relatively permanent traces that persist even when not being actively
maintained whereas the latter involves transient traces that decay rapidly in the absence of
attention (Baddeley, 2003). Recently multiple lines of evidence have pointed to the role long-
term memory in complex span tasks. For example, as with long-term memory tasks (Craik,
Govoni, Naveh-Benjamin, & Anderson, 1996; Craik, Naveh-Benjamin, Ishaik, & Anderson,
2000; Fernandes & Moscovitch, 2000; Guez & Naveh-Benjamin, 2006; Naveh-Benjamin &
Guez, 2000), complex span tasks require considerable attentional resources during retrieval, a
finding inconsistent with the view that the memoranda are stored in an active, easily retrieved
state (Healey & Miyake, 2009). As well, there is evidence that individuals who perform well on
complex span tasks also tend to perform well on a variety of long-term memory tasks (Unsworth,
2009; Unsworth & Brewer, 2009), again inconsistent with the view that the two types of tasks
measure different memory systems.

There is also evidence that long-term memory processes contribute to complex span
tasks’ ability to predict fluid intelligence. Recent work suggests that the reason complex but not
simple span tasks correlate with fluid intelligence is not that complex span tasks combine both
storage and processing, but rather that complex span tasks place greater demands on long-term
memory retrieval. For example, while simple span tasks do not correlate highly with fluid
intelligence when the list of to-be-remembered items is short, correlations begin to emerge as list
length increases (and presumably the need for long-term memory increases), reaching the level
of complex span/fluid intelligence correlations by list length six (Unsworth and Engle, 2006).
More evidence of the importance of long-term memory processes for the predictive utility of
complex span comes from structural equation modeling studies that examined the interrelations
among span, traditional long-term memory tasks, and fluid intelligence. Mogle et al. (2008) gave
participants several standard complex span tasks and a fluid intelligence task along with three
long-term memory tasks (a 20 word free recall task, a task that required reading a story and remembering the details, and a paired associate task). They found the usual correlation between the complex span tasks and fluid intelligence \((r = .42)\), but this correlation was actually lower than the correlation between the long-term memory tasks and fluid intelligence \((r = .58)\). Most tellingly, after statistically controlling for variation in long-term memory tasks, *complex span no longer predicted fluid intelligence*. Unsworth, Brewer, and Spillers (2009) conducted a similar study replicating the strong correlations between long-term memory tasks and fluid intelligence and also found that long-term memory tasks partially, though not fully, accounted for the complex span/fluid intelligence relationship.

Although there is an emerging consensus that long-term memory contributes to both complex span performance and fluid intelligence, the processes that underlie that contribution are not known. Here I consider the possibility that individual variation in interference control, a process critical for successful performance on memory tasks (both long-term memory and working memory) contributes to individual differences on complex span and fluid intelligence tasks.

*The contribution of Interference control*

Interference occurs when a cue to retrieve a memory (e.g., a question in a conversation, a self-generated thought, or a cue in an experiment) elicits multiple representations or possible responses. Proactive interference occurs when an older memory interferes with the retrieval of a newer memory, whereas retroactive interference occurs when a newer memory interferes with an older memory. It has been known for decades that interference between memory traces is one of the major limiting factors in long-term memory retrieval (e.g., Keppel, 1968; Postman & Underwood, 1973; Watkins & Watkins, 1975). Consistent with the view that span tasks depend
on long-term memory, recent research has shown that span tasks, which typically involve multiple trials with similar memoranda, are also highly sensitive to proactive interference (see Bunting, 2006; May, Hasher, & Kane, 1999; Rowe, Hasher, & Turcotte, 2008). For example, lowering the influence of proactive interference on complex span scores by placing the trials that have the largest impact on the final span score (i.e., those with the most to-be-remembered words) at the beginning of the task, before much proactive interference has built up, increases performance, especially for older adults who are highly susceptible to interference (May et al., 1999; Rowe et al., 2008). There is also evidence that performance on the reading span task, a complex span task that requires remembering target words while reading sentences, is lowered simply by having participated in a prior experiment (Lustig & Hasher, 2002), a finding that is consistent with work showing that serving in prior experiments disrupts performance on the most recent long-term memory task (Underwood, 1957).

Given that interference occurs in both complex span and long-term memory tasks, interference control mechanisms are a good candidate for examining the contribution of long-term memory processes to complex span. Indeed, many have argued that individual differences in the ability to control interference are a key contributor to individual and group differences in complex span tasks and other cognitive abilities (Awh & Vogel, 2008; Dempster, 1991; Gazzaley et al., 2005; Hasher & Zacks 1988; Hasher et al., 2007; Hasher et al., 1999; Jonides & Nee, 2006; Kane et al., 2007). At least two sources of interference have been noted in the literature, irrelevant information that occurs along with relevant information (Awh & Vogel, 2008; Hasher et al., 1999) and previously but no longer relevant information (Hasher et al., 1999; 2007). Both of these sources correlate with span: The reading with distraction task, a measure of ability to ignore concurrent distraction, correlated well ($r = .54$) with a composite of several complex span tasks (Darowski, Helder, Zacks, Hasher, and Hambrick, 2008). Friedman &
Miyake (2004) found that a latent variable labeled “resistance to proactive interference” (i.e., interference from no longer relevant information) was related to the reading span task ($r = -.40$).

The Role of Interference Regulation in the complex span/fluid intelligence relationship

Given that interference regulation is a powerful determinant of performance on complex span tasks, the critical question is whether interference regulation also makes a contribution to fluid intelligence. Indeed, it is possible that the need to control interference is ubiquitous in complex cognitive tasks. For example, fluid intelligence tasks frequently involve interference from salient but incorrect alternative solutions either because the task explicitly presents incorrect solutions as distractors or because participants think of answers to previous problems or generate incorrect answers, which they cannot easily reject, while trying to arrive at the correct one (see Dempster, 1991 for a similar argument about the role of interference control in reasoning tests). Several studies have shown that the need to control interference does indeed contribute to the correlations between complex span and fluid intelligence. Bunting (2006) manipulated the buildup of proactive interference in operation span by changing (or not) the type of memoranda (from words to digits) both within and across trials. Unsurprisingly, releasing interference by changing the memoranda increased span scores but, critically, releasing interference also simultaneously lowered correlations with fluid intelligence. That is, it is only when interference is high, and therefore demands on interference control processes are also high, that span predicts fluid intelligence. Lustig, May, & Hasher (2001) reported similar findings for the reading span task and story memory.

Other evidence on the relationship between interference control and fluid intelligence is less straightforward, perhaps due to the terminology used to describe interference control tasks. In many studies tasks that require interference control are labeled as ‘inhibition’ tasks on the
assumption that interference is resolved through inhibition (see the second part of this thesis for more on mechanisms of interference resolution). However, there are multiple types of interference and the mechanisms for controlling these different types may or may not be the same. For example, interference can come from competition between several memory traces that match a cue, or from distracting stimuli in the environment, or from strong but inappropriate response tendencies (e.g., reading words rather than naming colors in a Stroop task). Much of the existing work on the relationship between interference regulation and fluid intelligence has focused not on memory interference but on restraining strong response tendencies. For example, Friedman et al. (2006) administered several ‘inhibition’ tasks (antisaccade, Stroop, and stop-signal) and found they did not correlate with fluid intelligence as measured by Raven’s matrices and a block design task. In another study, Miyake et al. (2000) found that a latent variable composed of the same tasks was correlated with some fluid intelligence related tasks (the Tower of Hanoi task and a random number generation task), but not with others (the Wisconsin Card Sorting task); this latent variable was also not correlated with operation span (c.f., Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003; McVay & Kane, 2009).

From a theoretical standpoint, it makes some sense that motor restraint tasks such as antisaccade should be only weakly related to fluid intelligence and complex span. That is, if the role of interference control in fluid intelligence and complex span is to restrict attention to task relevant information (e.g., candidate solutions but not already rejected solutions in tasks like Ravens, current but not previous trial words in complex span tasks), then tasks that require restraining motor responses may not be the most appropriate measures (see Nigg, 2001 for a similar point). By contrast with the lack of correlation between motor restraint tasks and fluid intelligence, Friedman et al. (2006) found strong correlations between fluid intelligence and a latent variable that closely resembles the present conception of interference control; all of the
tasks contributing to the latent variable (letter memory, spatial 2-back, and keeping-track) involve the requirement to maintain access to a continuously changing set of stimuli (e.g., the last 2 items in a 2-back task to allow for detection of 2-back matches) a process that requires the ability to limit interference from previously relevant but currently irrelevant information. Hull, Martin, Beier, Lane, & Hamilton (2008) reported that a latent variable composed of a similar set of tasks was a strong predictor of two measures of fluid intelligence (Tower of Hanoi and Wisconsin Card Sort task) in a group of older adults.

In summary, complex span tasks have proven to be an extremely productive research tool, particularly in the individual differences field, and have been shown to be correlated with measures of fluid intelligence. However, it is an open question as to what cognitive processes complex span tasks actually measure and which of these processes is critical in predicting fluid intelligence. Recent evidence suggests that retrieval from long-term memory makes an important contribution to complex span task performance, which raises the possibility that interference regulation, a process known to be critical in long-term memory, plays a role in the correlation between complex span and fluid intelligence. In Study 1 of this thesis I consider the role of interference regulation abilities in the relationship between complex span tasks performance and fluid intelligence. In Studies 2a and 2b I consider the mechanisms that underlie interference regulation, testing the theory that interference is resolved by suppressing competing information. Finally, in Studies 3a and 3b I test the hypothesis that older adults have an impaired ability to suppress competing information.
Chapter 2 Study 1

There is a growing consensus that complex span tasks are not pure measures of active maintenance in working memory. Long-term memory clearly makes a contribution to complex span, but it is not clear how much of a contribution. Similarly, it is clear that controlling interference is critical to both complex span and long-term memory tasks. However, the interplay among complex span, long-term memory, and interference control in predicting fluid intelligence is not known. Here I aim to draw together these loose threads in the memory and individual differences literature. I do so by administering measures of all four constructs - complex span, long-term memory, interference control, and fluid intelligence - and using structural equation modeling to address two major questions: (1) to what extent do individual differences in long-term memory performance account for the relationship between complex span and fluid intelligence, and (2) can interference control ability account for the relationship between the memory variables and span?

Method

Participants

One hundred and two students (60 females) from Michigan State University participated for monetary compensation. Participants were 18 to 28 years old ($M = 19.71, SD = 1.66$), fluent English speakers, with normal color vision, and normal or corrected to normal visual acuity.

Tasks and Procedure

One of the challenges in studying individual differences is that any particular task is likely to require multiple cognitive processes. This lack of process purity poses a serious problem when interpreting correlations between single tasks. The correlation between complex span...
span tasks and fluid intelligence is a perfect example: if operation span correlates with Ravens (a common fluid intelligence measure), is it because they both require working memory, long-term memory, interference control, or some other construct? A principal advantage of structural equation modeling is the ability to circumvent this lack of process purity by using several tasks to converge on one construct. When several tasks are used to define a latent variable, variance shared between the tasks is extracted, or “taken up” by the latent variable, and any variance not shared between the tasks is “left behind”, making no contribution to the latent variable (Miyake et al., 2000). Therefore, as long as only a single construct is measured by all of the tasks contributing to a latent variable, it is not a problem if a subset of the tasks overlap on more than one construct (e.g., two of the interference control measures used here involve a substantial memory demand, but the third does not). With this logic in mind, three tasks were selected as measures for each of the four constructs of interest - interference control, long-term memory, complex span tasks, and fluid intelligence - (see Table 1 for a list of the tasks and descriptive statistics). The ability of latent variable techniques to extract variance related to a construct of interest while “leaving behind” unrelated variability depends on selecting tasks that share construct related variability but do not share sources of non-construct related variability (e.g., variability from similar administration procedures or the use of similar stimuli). I attempted to select tasks with this principle in mind (with the exception of complex span tasks, which by definition share the same administration procedure; see the discussion for more on this issue).

The tasks, which are described in detail below, were completed in the following order: Session 1 – paired associates, Ravens matrices, sentence span, free recall, operation span, series completion, story memory, letter sets, and rotation span; Session 2 – reading with distraction, directed forgetting, and N-Back. Several other cognitive tasks, not relevant for present concerns, were also administered. Participants were tested individually in two sessions separated by
Complex Span Tasks

*Operation Span.* Modeled after Turner and Engle (1989), on each trial participants were presented with a set of words for serial recall while also solving math equations that were presented before each word. A trial proceeded as follows: An equation was presented on screen (e.g., “8/2+4=7”), participants read the equation aloud, and said “yes” or “no” to indicate if the provided solution was correct. A word then appeared below the equation for 1 sec (e.g., “SNOW”), participants read it aloud, and the experimenter advanced the program to the next equation/word pair. A trial consisted of 3, 4, 5 or 6 equation/word pairs; trials were presented in order of increasing set size with two trials at each size. After the final word for a trial had been read, a recall cue appeared and participants wrote the words, in order of presentation, on a response sheet with 6 blank spaces. Operation span scores were calculated following the recommendations of Conway et al. (2005): One point was assigned for each word recalled in the correct serial position but only if the corresponding equation was correctly solved. The total number of words recalled across all trials was summed to give the final span score.

*Sentence Span.* The sentence span task was identical to the operation span task except that instead of verifying equations, participants verified the coherence of sentences (e.g., “Karen spent the afternoon baking desks”). A sentence was presented, participants read it aloud, and verified its coherence (by saying “yes” or “no”). A target word, unrelated to the sentence, then appeared below the sentence for 1 sec and was read aloud. A trial consisted of 3, 4, 5 or 6 sentence/word pairs with two trials at each set size presented in ascending order of set size. Immediately after presentation of the last word in each trial, participants recalled the words by writing them in order on response sheets like those used for operation span. Sentence span scores

approximately 7 days.
were calculated in the same manner as operation span scores.

Rotation Span. Rotation span (based on the Letter Rotation task from Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) is designed to be a spatial analog of the verbal complex span tasks. It requires remembering several spatial stimuli (the orientation of arrows), the presentations of which are interleaved with a spatial processing task (mental rotation). On each trial an uppercase letter (G, R, or F) was presented in the center of a roughly circular “blob” shape. The letter was rotated from its usual upright position by some multiple of 45° and was either a normal letter or a mirror image version of a normal letter (i.e., rotated 180° around the vertical axis). The participants’ task was to indicate if the letter was a normal or a mirror image version by saying “yes” (normal) or “no” (mirror image). After the participant responded to the letter, an arrow was presented which originated from the center of the blob and pointed in one of 8 directions (i.e., 0°, 45°, 90°, 135°, 180°, 225°, 270°, or 315°). Participants were to remember the orientation of each arrow. A trial consisted of 3, 4, 5 or 6 letter/arrow pairs with two trials at each set size. Once all of the letter/arrow pairs for a trial had been presented, the participants were given a response sheet containing 6 blank “blob” shapes and recalled the orientations of the arrows in the order in which they were presented by drawing arrows in the blank “blobs”. Span scores were calculated as the number of arrows recalled in the correct serial position.

Long-Term Memory Tasks

Free Recall. I used the list-learning task from the Victoria Longitudinal Study (Dixon & de Frias, 2004). Participants studied two lists of 30 words drawn from 4 taxonomic categories presented in random order. Participants were shown a list and given two min to study with the instruction to remember as many words as possible for later recall. Immediately after the study period participants were given 5 min to recall as many of the words as possible, in any order, by
writing them on a response sheet. After studying and recalling the first list, participants began studying the second list. The dependent measure was the percentage of words correctly recalled across both lists.

**Story Memory.** This task was adapted from the Victoria Longitudinal Study (Dixon & de Frias, 2004). Participants were given 4 min to read a 24 sentence, 296-word story titled “A Visitor from France”. After reading the story, participants were given 10 minutes to recall, in writing, as much of the substance of the story as possible, including main ideas and details. Participants were told they could recall the story in their own words, those of the story, or any combination of the two. The story contained 160 propositions that ranged from main ideas to specific details. The dependent measure was the proportion of propositions recalled. In scoring recall I used the same criteria as Dixon and de Frias (2004).

**Paired Associates.** Modeled after Salthouse, Fristoe, and Rhee (1996), this task required participants to learn two 6-pair lists. The word pairs were 1- and 2-syllable common nouns. The experimenter read the pairs aloud pausing for 1 second between members of a pair and for 3 seconds between different pairs. Testing followed immediately. The participant was instructed that the experimenter would read the first member of each pair, and they would have 3 seconds to say aloud the second member of the pair. The dependent measure was the number of words correctly recalled across both lists.

**Fluid Intelligence Tasks**

**Ravens Matrices.** Each problem in the Ravens Advanced Progressive Matrices (Raven, 1965) requires the participant to select which of several options completes the pattern in a 3x3 matrix missing one cell. In the current study, participants first completed 2 practice problems and were then given 10 min to complete as many of 18 additional problems (the odd numbered items
from the full test) as possible. The dependent measure was the number of problems correctly solved within the time limit.

**Letter Sets.** This task, which was adapted from the Kit of Factor Referenced Tests (Ekstrom, French, & Harman, 1979), consisted of 15 problems each of which presented 5 sets of 4 letters each. For each problem, 4 of the sets followed some rule, which was violated by the 5th set. The task was to indicate which set violates the rule by circling it. For example, in the set “BVZC FVZG JVZK PWXQ SVZT” the set PWXQ violates the rule. Participants were given 7 min to complete as many of the problems as possible. The dependent measure was the number of problems solved correctly in the 7 min.

**Series Completion.** This task, from the Shipley Institute of Living Scale (Shipley, 1946), consisted of 20 problems, each of which presented a series of 3, 4, 5, 6 or 7 items that followed some pattern. Participants were required to provide the next item in the series. For example, the series “white-black, short-long down-____” would be completed with “up”, the series “escape, scape, cape, ____” would be completed with “ape”. The test started out with easy problems and increased in difficulty. Participants were given 4 min to solve as many of the problems as possible. The dependent measure was the number of problems correctly solved within the time limit.

**Interference control tasks**

As discussed above, there are at least two sources of cognitive interference: irrelevant information presented concurrently with relevant information, and previously relevant but no longer relevant information. Interference control tasks were selected that involve both concurrent distraction (Awh & Vogel, 2008; Hasher et al., 1999) and disruption from no longer relevant
information (Hasher et al., 1999; 2007) so that the resulting latent variable would reflect a
general ability to control interference.

Reading With Distraction. The reading with distraction task was adapted from Connelly, Hasher, and Zacks (1991; see also Darowski et al., 2008). On each trial, participants were asked to read aloud a paragraph of text that told a coherent story (e.g., of a student driving home for summer break). The relevant or target text (presented in italicized typeface) was interspersed with irrelevant text (presented in upright typeface). There were two within-subject conditions. In the low interference condition the irrelevant text was simply strings of X’s, whereas in the high interference condition the irrelevant text was related to the content of the target paragraph. Therefore, while both conditions required overcoming perceptual distraction, only the high interference condition required preventing conceptually similar information from accessing attention. After each story, participants answered four 6-alternative multiple-choice questions about the paragraph. The task began with a low interference trial followed by two high interference trials and finished with another low interference trial. The dependent measure, reading time (in seconds) in the high interference condition minus reading time in the low interference condition, indexes the efficiency of preventing the irrelevant text from accessing attention.

Directed Forgetting. I adapted the task from the version used by Zacks, Radvansky, and Hasher (1996). Participants were told that the task tests their ability both to remember and forget words. On each trial a list of 4, 6, or 8 words was presented (1300 ms per word with an 80 ms ISI). On control trials, each word was presented in the same color typeface. On directed forgetting trials, the color of the words changed (e.g., from blue to red) part way through the list, and participants were instructed that when such a change occurred they should forget the words
presented in the initial color and remember only words presented in the second color. After the final word in a list, there was a 3000 ms blank screen followed by a probe word presented in black typeface. Participants indicated if the probe was one of the to-be-remembered words by pressing a key. There were three types of probes: new probes had not been presented in the list; to-be-remembered (TBR) probes that occurred anywhere on a control trial or after a color change on a directed forgetting trial; to-be-forgotten (TBF) probes that occurred before the color change on a directed forgetting trial, and thus are irrelevant and a potential source of interference. The task began with 3 practice trials followed by 48 experimental trials. Twenty-four of the experimental trials presented TBR probes, 12 presented TBF probes, and 12 presented new probes. The words were medium frequency nouns, with unique words being used for each list. The dependent measure was the number of false alarms to TBF words (i.e., indicating a word was on the to-be-remembered list when it was supposed to be forgotten), a measure of the ability to control interference from TBF words while trying to recall TBR words.

*N-back.* In this task participants viewed a series of upper and lowercase letters (selected from all the consonants except L, W, and Y) presented for 500 ms each, followed by a blank screen for 2500 ms. For each letter, participants had to press one key if it matched the letter presented 2-back in the series, and another key if it did not match. In addition to 2-back matches, on critical trials the letter matched the letter 3-back (3-back lures); items 3-back in the list can never be 2-back matches and are thus a source of potential interference. The task began with a 45-letter practice block, followed by two 45 letter experimental blocks. Across the two experimental blocks there were 39 mismatches (i.e., the letter had not appeared within at least the last six items), 27 2-back matches and 17 3-back lures. If interference control is operating efficiently, items 3-back in the list should have been excluded from consideration making false
alarms to 3-back lures unlikely and participants should correctly reject most lures; therefore, the dependent measure used was number of correct responses to 3-back lures.

Data Preparation and Analyses

Table 1 shows the descriptive statistics and raw correlations for the tasks. Reliability estimates were calculated for each task and are shown in the bottom section of Table 1 along with details on the calculation method. Confirmatory factor analysis and SEM techniques are sensitive to deviations from multivariate normality; such deviations can, however, be reduced by ensuring all univariate distributions are normal and free of extreme outliers (Kline, 2005). I employed a two-step procedure to ensure normal, outlier free distributions. First the distribution for each measure was examined and, if necessary, transformed to achieve normality\(^2\). Second, to deal with any outliers remaining after step 1, values more than 3 standard deviations from the variable mean were replaced with the most extreme non-outlying value in the distribution. To ease interpretation of the parameter estimates reported below, before fitting the models the measures were adjusted so larger numbers indicate better performance (e.g., superior interference control ability).

\(^2\) Depending on the shape of a non-normal distribution, different transformations are effective at achieving normality. I therefore selected transformations for each measure individually. Table 1 shows which transformation, if any, was carried out on each measure. I also fitted all of the models reported here to data that was trimmed to 3 SDs but not transformed. While there are some differences in the exact parameter estimates between the models fitted to transformed and untransformed data, the patterns of correlations between latent variables are similar and both sets of estimates support the conclusions drawn here.
Ten additional participants were tested, but their data were excluded from analysis because they failed to complete properly 3 or more of the tasks (due to experimenter error, equipment failure, or failure to return for the second session). Of the remaining 102 participants, 2 were missing data (1 missing variable per participant). These missing values were replaced using the regression estimation method in SPSS’s missing value analysis procedure\(^3\). The models were fit using the maximum-likelihood estimation procedure in AMOS (Arbuckle, 2007). I report a range of indices of model fit. In addition to the standard model chi-square (\(\chi^2\)), which indexes the difference between the observed and reproduced covariance matrices, I report the chi-square divided by the degrees of freedom (\(\chi^2/df\)); generally \(\chi^2/df\) values less than 2 are seen as indicating good fit. The Root Mean Square Error of Approximation (RMSEA) is the square root of the average squared difference between the observed and implied covariances, smaller values indicate better fit; values less than .08 indicate acceptable fit. The comparative fit index (CFI) and the non-normed fit index (NNFI) both measure the extent to which the proposed model improves on a baseline model; values above .9 indicate good fit.

Results

The first step was to conduct a confirmatory factor analysis, specifying separate latent variables for each of the constructs - complex span, long-term memory, fluid intelligence, and interference control. The resulting model, shown in Figure 1, fits well (see Table 2 for the fit indices of this and all other models reported here) and all tasks loaded significantly onto their

\(^3\) The procedure estimates a missing value on a particular variable based on a regression with the other variables as predictors; it then takes the predicted value and adds an error component by adding the residual from a randomly selected non-missing observation.
respective latent variables. I draw your attention to three aspects of the model. First it replicates
the well established relationship between complex span and fluid intelligence; second it
replicates the recent findings that long-term memory tasks are closely related to both complex
span and fluid intelligence (Mogel et al., 2008; Unsworth et al., 2009); and finally it shows that
interference control has strong to moderate relationships with complex span, long-term memory,
and fluid intelligence.

Next I conducted a series of SEM analyses to test specific hypotheses about the
relationships among the constructs. The first analysis addresses the question of whether or not
variation in long-term memory tasks can account for the correlation between complex span tasks
and fluid intelligence. If long-term memory explains the span/fluid intelligence relationship, then
when controlling for the influence of long-term memory, span should no longer correlate with
fluid intelligence, but when controlling for the influence of span, long-term memory should still
correlate with fluid intelligence (Barron & Kenny, 1986). I tested this prediction with a structural
equation model specifying direct effects of both span and long-term memory upon fluid
intelligence. If long-term memory accounts for all of the variance shared between span and fluid
intelligence then the direct effect of span on fluid intelligence should be greatly reduced relative
to the overall correlation (.44 from Figure 1) between complex span and fluid intelligence. The
resulting parameter estimates are shown in Figure 2. The relationship between span and fluid
intelligence drops considerably, however the relationship between long-term memory and fluid
intelligence remains high. Indeed, setting the path from complex span to fluid intelligence to zero
did not reduce model fit (\( \Delta \chi^2(1) = 0.13, p > .05 \)). These results suggest that variation in long-
term memory tasks fully account for the relationship between span and fluid intelligence. Note
that the current results are consistent with Mogle et al.’s (2008) finding that long-term memory
fully accounted for complex span/fluid intelligence correlation (but see Unsworth et al., 2009).
I have proposed that interference control mechanisms contribute variance to both complex span tasks and fluid intelligence. This view predicts that controlling for variation in interference regulation should reduce or eliminate the span/fluid intelligence relationship; much the same as controlling for long-term memory did in the previous analysis. I tested this prediction by fitting the model shown in Figure 3. As predicted, the direct effect of complex span on fluid intelligence was considerably smaller (.18) than the corresponding path in Figure 1 (.44) and model fit was not harmed by setting the path to zero ($\Delta \chi^2(1) = 1.41, p > .05$), indicating that variation in interference control ability largely accounts for the span/fluid intelligence relationship.

Given that both interference control and long-term memory can account for the complex span/fluid intelligence correlation, the next question is the extent to which interference control and long-term memory make overlapping versus unique contributions. That is, can variation in interference control ability fully account for the predictive utility of long-term memory (or vice versa). To address this question, I fit the model shown in Figure 4; it specifies direct paths from all three possible predictors, span, long-term memory, and interference control, to fluid intelligence. If any latent variable does not contribute unique variance to fluid intelligence, its path should drop to near zero. Consistent with models 2 and 3, the span to fluid intelligence path dropped from its value in Figure 1 (.44) and could be set to zero without significantly reducing fit ($\Delta \chi^2(1) = 0.04, p > .05$). The paths from long-term memory to fluid intelligence and from interference control to fluid intelligence dropped numerically from their values value in Figure 1 (.76 and .83 respectively) but remained reasonably high, although the path for long-term memory did not reach standard levels of significance ($p = .16$). Given that complex span makes no contribution to fluid intelligence, I removed it to simplify the model (see Figure 5). Again,
interference control made a large contribution to fluid intelligence, but the long-term memory path was non-significant at conventional levels \((p = .10)\). However, given that the long-term memory to fluid intelligence path was reasonably high, numerically, and approaching conventional significance levels, suggests that while interference control is critical, non-interference related long-term memory processes may make a small contribution to fluid intelligence. Together these results suggest that interference control is strongly related to fluid intelligence and largely explains the relationship of both complex span and long-term memory tasks with fluid intelligence.

**Study 1 General Discussion**

This study had two main aims. The first was to determine the extent to which individual differences in long-term memory can account for the correlation between complex span and fluid intelligence. The results are straightforward: After controlling for variability in long-term memory tasks, complex span tasks no longer predicted fluid intelligence. The second aim was to determine the role of interference control in the relationships among complex span, long-term memory, and fluid intelligence. Again, the results are straightforward: Interference control fully accounted for the complex span/fluid intelligence correlation. These findings suggest that both complex span and fluid intelligence rely heavily upon interference control.

*The contribution of long-term memory*

Recent evidence that long-term memory contributes to performance on complex span tasks raises the question of the extent to which long-term memory itself accounts for the correlation between span and fluid intelligence. The present findings are consistent with those of Mogle et al. (2008) who reported that controlling for variation in long-term memory completely eliminated the span/fluid intelligence correlation. They contrast, however, with those of
Unsworth et al. (2009) who found that complex span still predicted fluid intelligence after controlling for long-term memory. It seems likely that there are as yet unknown factors that account for the similarities and differences among the findings of the three studies. For example, there are multiple differences in the long-term memory tasks used in the studies such as the type of memoranda, list length, test type (recall, recognition), and the similarity of materials across tasks (a variable that increases interference). Experimental studies manipulating factors such as level of interference will help determine the circumstances under which complex span predicts fluid intelligence above and beyond long-term memory. It is, however, clear that in all three studies long-term memory makes a large contribution to the relationship between complex span and fluid intelligence.

The role of interference control

Understanding why memory tasks predict fluid intelligence requires determining what the cognitive processes are that are shared among long-term memory, complex span, and fluid intelligence. I examined the role of interference control based on evidence that interference is a limiting factor in many aspects of cognition, including attention and perception (e.g., Barense, Gaffan, & Graham, 2007; Barense, Rogers, Bussey, Saksida, & Graham, 2010; Kane et al., 2007; Peterson & Skow, 2008), and especially in complex span and long-term memory performance (Bunting, 2006; Hamm & Hasher, 1991; Lustig et al., 2001; May et al., 1999; Rowe et al., 2008). I found that interference control was strongly related to fluid intelligence and controlling for interference regulation ability essentially eliminated the complex span/fluid intelligence relationship. Controlling for interference regulation also substantially reduced the relationship between long-term memory and fluid intelligence tasks, suggesting that interference regulation is an important component of both types of tasks. This study demonstrates the importance of
interference control, but other long-term memory processes may also play a role in fluid intelligence. For example, the ability to self-generate retrieval cues may also be a limiting factor in both memory recall (e.g., Craik et al., 1996) and fluid intelligence.

Why does interference control predict fluid intelligence? On the surface, interference control and fluid intelligence tasks are very different. However, at a process level, many fluid intelligence tasks require control over irrelevant information, whether it be previously considered but rejected candidate solutions, distractors in multiple choice problems, or the solutions to prior problems (Dempster, 1991). Success on fluid intelligence tasks likely also requires control over mind wandering; self-generated thoughts that are irrelevant to the task at hand (e.g., McVay, Kane, & Kwapil, 2009). Similar arguments can be made for other tasks commonly found to correlate with complex span. For example, reading comprehension likely requires control over irrelevant or misleading information (e.g., Carretti, Cornoldi, De Beni & Romanò, 2005). Distraction is a ubiquitous aspect of our mental lives. As such the ability to control both external and self-generated distraction may be an extremely powerful cognitive primitive.

**Complex Span: Task or Construct?**

Complex span is a type of task, but it is often thought of as measuring working memory capacity. In many individual difference studies, complex span tasks are the only type of tasks used to define latent variables labeled working memory, or working memory capacity. The present data suggest that complex span tasks do not define any single psychologically valid construct, but rather measure multiple constructs, such as interference control and perhaps other long-term memory processes. From a methodological perspective the multifaceted nature of complex span tasks suggest that they must be combined with other types of tasks to converge on putative underlying constructs such as working memory. The increasing use of working memory
capacity as an explanatory construct in psychology and related fields such as anthropology (e.g., Coolidge & Wynn, 2007) underlines the importance of developing a clear understanding of what cognitive processes actually determine performance on complex span tasks so we can define underlying constructs with greater precision.

A broader question is whether the separation between long-term memory and working memory (as assessed by complex span tasks) is psychologically meaningful. Data such as those presented here and by Mogel et al. (2008) suggest that the distinction is not meaningful, at least in terms of predicting fluid intelligence (but see also Unsworth et al., 2009). Elsewhere in the memory literature there is active debate over whether working memory (or short-term memory) and long-term memory are actually distinct systems (e.g., Bhataraj, Ward, & Tan, 2008; Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Olson, Moore, Stark, & Chatterjee, 2006; Oztekin, Davachi, & McElree, 2010; Polyn, Norman, & Kahana, 2009; Postle, 2006; Sederberg, Howard, & Kahana, 2008; Usher, Davelaar, Haarmann, & Goshen-Gottstein, 2008). Some theorists argue that information is encoded into and retrieved from the same store regardless of retention interval (e.g., Polyn et al. 2009), while others argue that some mechanism for privileging a small number of traces over short intervals is necessary (e.g., Davelaar et al. 2005). The issues raised in these debates have begun to influence working memory research (e.g., Healey & Miyake, 2009; Oberauer & Lewandowsky, 2008; Unsworth, 2009) but given the now clear role of long-term memory in fluid intelligence, much theoretical ground can be gained by more fully delineating the similarities and differences between complex span tasks and traditional long-term memory tasks.
Conclusion

Complex span tasks have enjoyed considerable popularity in large part due to their ability to predict fluid intelligence. The tasks were designed to measure the ability to store information in an accessible state while simultaneously processing other information, an ability thought to be critical in determining fluid intelligence (Kane et al., 2007). However, it has become apparent that complex span tasks also require retrieval from long-term memory. The present findings show that long-term memory, particularly the ability to control interference, accounts for much, perhaps all, of the predictive utility of the most widely used complex span tasks.

While it remains a matter of debate whether complex span tasks measure short or long-term memory (or if the short/long-term distinction is necessary at all), there is a growing consensus that cognitive performance is facilitated by having the focus of attention be narrowly engaged with those elements that are task relevant and hindered if attention is too broadly focused to include irrelevant elements (Bunting, 2006; Hasher et al., 2007; Kane et al., 2007; Lustig et al., 2001; May et al., 1999; Jacoby, Shimizu, Velanova, & Rhodes, 2005; Jarrold & Towse, 2006). The outstanding question, which will occupy the second major section of the thesis, is how a narrow focus is achieved.
Chapter 3 Mechanisms of Interference Control

How is interference controlled to allow for a narrow focus on task relevant or target information? Hasher and Zacks (1988; see also Hasher et al., 2007; Hasher et al., 1999) have argued that the most important processes (in terms of group and individual differences) in achieving a narrowly focused working memory are inhibitory.

Conceptually, successful interference resolution requires making the target response more accessible relative to the competing responses. Many researchers (M.C. Anderson & Spellman, 1995; Bjork, 1989; Hasher et al., 2007; Hasher et al., 1999; Postman & Underwood, 1973; Zanto & Gazzaley, 2009) have argued that the resolution of interference entails the suppression or inhibition of competing information. Suppression makes target information more accessible relative to competing information indirectly, by making interfering information less accessible. That is, suppression does not change the absolute accessibility of target information, only its accessibility relative to competitors. An alternative theory, however, is that interference is resolved by facilitative processes, which directly enhance the absolute accessibility of target information (e.g., J.R. Anderson et al., 2004; J.R. Anderson & Reder, 1999). Under a purely facilitative view, interference resolution processes act directly on target information, leaving the absolute accessibility of competitors unchanged. A third possibility, which will be explored below, is that suppression and facilitation operate in concert to produce an accessibility differential between targets and competitors.

These competing theories are difficult to test, as inhibitory and facilitative mechanisms predict similar outcomes: If either mechanism is successful, the target memory is recalled (see MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003). Thus, the mechanisms underlying interference resolution remain an area of active debate (e.g., Jonides & Nee, 2006). The studies presented in
this section of the thesis provide direct evidence that resolving interference during memory retrieval involves the suppression of competing responses.

One distinguishing feature of suppression is that it acts not on targets but on competitors. By making competitors less accessible, suppression increases the relative accessibility of target information. Therefore, we would expect a fingerprint of suppression to be reduced accessibility of competing responses following interference resolution. I tested this prediction by having participants in an experimental condition resolve interference between targets and competitors in an implicit memory task and then measuring both competitor accessibility (Study 2a) and target accessibility (Study 2b).
Chapter 4 Study 2a

The procedure, based on that used by Ikier, Yang, and Hasher (2008) to examine interference in implicit memory, has three consecutive phases. In the interference condition (Figure 6, first column), Phase 1 creates the potential for interference by embedding pairs of orthographically similar words (e.g., allergy and analogy) in a vowel-counting task. As the task is intended to measure implicit memory, the presentation of pair members was separated by the presentation of multiple filler words to reduce the chance of participants noticing the connection between pair members (see below for more detail). Phase 2 encourages interference resolution, as participants solve word fragments that resemble both words in a pair (e.g., a _ l _ g y), but can be completed only by a target word (allergy) and not by its competitor (analogy). If the interference between target and competitor is resolved by suppressing the competitor, competitor accessibility should be reduced. Conversely, if interference is resolved by facilitating the target, target accessibility should be increased. In Phase 3, competitor (Study 2a) and target (Study 2b) accessibility is tested with a naming task. The amount of time that a participant takes to name the critical word in the interference condition is then compared with the time taken to name it in several control conditions. In the no-resolution condition (Figure 6, second column), participants are presented in Phase 1 with target words and competitor words that cannot be used to complete any of the word fragments in Phase 2. This condition controls for the possibility that accessibility of competing memories (competitor words) is reduced by the potential interference created in Phase 1, and not by suppression during interference resolution in Phase 2. In the no-conflict condition (Figure 6, third column), participants are presented in Phase 1 with competitor words but not the corresponding targets. This provides a measure of naming time (or priming) in the absence of either potential interference at encoding or conflict resolution at retrieval. All of these
conditions were compared to a baseline condition in which participants simply named the critical words without any prior, experimental-session exposure to them. As detailed in the Results section for Study 2a, participants in the interference condition were slower to name competitors than participants in either control condition, a pattern confirming that selection in the face of competitors entails suppression of competitors. Study 2b revealed that suppression of competitors was not accompanied by facilitation of targets.

Method

Participants, materials, and procedure

One hundred forty-one introductory psychology students from the University of Toronto (fluent English speakers since at least the age of 5) participated in Study 2a in exchange for course credit. The paradigm consisted of 3 phases. Participants in the interference, no-resolution, and no-conflict condition completed all three phases, while participants in the baseline condition completed only Phase 3.

Phase 1: encoding. During Phase 1, Participants viewed 56 words, including (in the interference and the no-resolution conditions) 15 target words and 15 competing words, and reported aloud the number of vowels in each word. Two lists of 15 target-competitor pairs were created; see the appendix for the actual pairs. Target words and their competitors were of the same length, began with the same letter, and shared on average 3.3 letters in corresponding positions (cf. $M = 0.5$ shared letters between target words and filler words). Orthographic similarity was minimized between nonpaired words, both within and across the two lists.

Participants in the interference condition and the no-resolution condition were shown targets and matching competitors (half of the participants were shown List 1 pairs, and the other half were shown List 2 pairs). Rather than being shown matching targets and competitors, Participants in the no-conflict condition were shown targets from one list and competitors from
the other list (e.g., rather than allergy/analogy, no-conflict target/competitor pair would be liberty/analogy, see Figure 6). In all conditions, I presented the following sequence of stimuli in Phase 1: 3 buffer words, followed by 15 competitor words randomly mixed with 10 filler words, then 15 target words randomly mixed with 10 fillers, and finally 3 buffer words. Filler words were similar in frequency and length to the target and competing words, but semantically and lexically dissimilar. Each word was shown for 1,800 ms, followed by a 1,000-ms interstimulus interval (ISI). Phase 1 was followed by a 6-min filler task, in which participants provided the missing digits in equations.

**Phase 2: retrieval.** In Phase 2, participants were given 36 word fragments, including 15 critical fragments (e.g., a_1_ _gy) that could be completed only by a target word (e.g., allergy), and not by the corresponding competitor (e.g., analogy). The target words seen in Phase 1 could be used to complete the critical word fragments in the interference and no-conflict conditions, but not the word fragments in the no-resolution condition. Participants viewed each fragment for 4,500 ms (followed by a 500-ms ISI) and responded aloud with a word they thought would complete the fragment. The 15 target-word fragments were presented with 15 randomly interspersed filler fragments. In addition, 6 buffer-word fragments were presented: 3 at the beginning of the task and 3 at the end of the task.

In summary, participants in the interference condition solved word fragments for which they had seen the correct solution, as well as an orthographically similar competitor. Thus, correctly solving the critical fragments required that the participants resolve interference between the solution word and the competing word. Participants in the no-resolution condition also saw targets and their competitors in Phase 1. This condition therefore created the potential for interference, but none of the word fragments in Phase 2 required participants to resolve that interference. Participants in the no-conflict condition solved word fragments for which they had
seen only target words in Phase 1, and thus should have experienced little target-competitor interference.

**Phase 3: naming.** In Phase 3, participants read 33 words aloud as quickly as possible. Each word was presented until a response was given and was followed by a 1,500-ms ISI. A voice key recorded reaction time (RT). This test list began with 3 buffer words, followed by the 15 competitor words (used in Phase 1) mixed with 15 new words (roughly matched to the competing words in length and frequency of occurrence). We expected that if participants in the interference condition suppressed competitor words during the fragment-completion phase, the competitor words would be less accessible than if they had not been suppressed (as in the two control conditions). Evidence of such suppression would be slower reading of competitor words by participants in the interference condition than by participants in either the no-resolution condition or the no-conflict condition. Finally, I included a baseline condition in which participants completed only the Phase 3 word-naming task, without completing Phase 1 or Phase 2 (i.e., without having had any laboratory exposure to the target or competitor words).

**Data analysis**

Because the paradigm was designed to measure implicit memory, I was concerned about including data from participants who became aware of connections among the phases of the study. If a participant becomes aware of connections between the tasks, their approach to the tasks may change in unpredictable ways. For some participants, awareness may lead them to explicitly try to recall Phase 1 words in Phase 2, or perhaps to slow down during the naming task, while for other participants awareness may have little effect. Therefore, awareness may serve to increase variability in how participants approach the tasks and so add noise to the data. Thirty-seven participants reported some awareness that words had repeated across the phases of the study (as determined by a graded awareness questionnaire, which progressed from general
questions such as “Did you notice any connection between the tasks?” to specific questions such as “Did you notice that some words repeated throughout the tasks?”), and these participants were therefore eliminated from analyses.

I excluded any trial on which the participant failed to read a critical word or read it incorrectly (5.03% of all observations). For participants in the interference condition, I included in the analyses only competitors for which the participant had correctly solved the corresponding word fragment during Phase 2, as failure to solve the word fragment could indicate that suppression was not successful (and competitor naming might therefore not be slowed). To ensure reliable estimates of word naming times, I excluded data from four participants with fewer than 6 usable RTs (usable RTs are those for which the participant correctly named the word and, for interference participants, correctly solved the corresponding fragment). Including these participants in our analyses did not change the outcome of any of the significance tests. The remaining 100 participants provided 6 to 13 usable competitor-word RTs ($M = 7.7$). To minimize the influence of nonnormal distributions and outlying observations (Erceg-Hurn & Mirosevich, 2008), I winsorized the naming RT data by 5% and then calculated a mean RT for each word type for each participant. Winsorizing corrects for outliers and non-normal distributions in a single step while preserving the original meaning of the units by trimming a certain proportion (5% here) of the total observations from the tails of the distribution and replacing them with the most extreme untrimmed scores.

\[4\] The pattern of results was qualitatively identical for untrimmed data.
Results

If seeing both the target words and the competitor words during Phase 1 (as in the interference condition) produced interference during fragment completion, participants in the interference condition should be more likely to intrude the competitors during fragment completion (i.e., producing the competitor word rather than the correct target word) than no-conflict participants who had seen only the target during Phase 1. Confirming the success of the interference manipulation, interference participants produced on average 2.27 competitor intrusions ($SEM = 0.23$) whereas no-conflict participants produced an average of only 0.14 competitor intrusions ($SEM = 0.10$), $t(52) = 8.63, p < .01$. As an additional check of the interference manipulation, I examined overall fragment completion accuracy. Participants in the interference condition solved on average 8.04 ($SEM = 0.27$) critical word fragments, reliably fewer than the 8.96 ($SEM = 0.33$) critical word fragments solved by participants in the no-conflict condition, who saw only targets in Phase 1, again confirming that the seeing both targets and competitors in Phase 1 produced interference. Participants in the no-resolution condition, who saw word fragments unrelated to any words from Phase 1, solved an average of 7.08 ($SEM = 0.36$) critical fragments, providing a baseline measure of fragment completion without any exposure to the target words. Participants performed above this baseline in both the interference condition, $t(48) = 2.13, p = .039$, and the no-conflict condition, $t(50) = 3.87, p < .001$. In other words, having seen a target in Phase 1 helped participants complete word fragments in Phase 2, but having seen the corresponding competitor as well as the target word created interference, reducing the benefit of having seen the target.

Table 3 and Figure 7a shows participants' mean naming times for competitor words and new words. There were no differences among the conditions (interference, no-resolution, no-conflict, and baseline) in naming times for new words, $F(3, 96) < 1$. The naming times for
competing words indicated that resolving interference entailed suppressing those words: Interference-condition participants were slower to name competitors than no-resolution participants and no-conflict participants. Analyses of covariance (ANCOVAs) were carried out on competitor naming times, with new-word naming times as the covariate to control for between-subjects variability in naming time. Competitor words were named more slowly by interference participants than by either no-resolution participants, $F(1, 47) = 4.98, p = .03$, or no-conflict participants, $F(1, 51) = 5.53, p = .02$, a finding consistent with the hypothesis that suppression is the source of interference resolution.

By comparing naming time in the baseline condition with naming time in the other conditions, it is possible to assess the extent of suppression. In all conditions except the baseline condition, participants had seen the competitor words in Phase 1 prior to naming them in Phase 3. I therefore expected that in the absence of any suppression, participants would show priming; that is, they would name competitor words in these conditions more quickly than in the baseline condition. I observed such a priming effect in both the no-resolution condition, $F(1, 43) = 9.92, p < .01$, and the no-conflict condition, $F(1, 47) = 8.30, p < .01$, but not in the interference condition, $F(1, 45) < 1$. Thus, the suppression applied during interference resolution was sufficient to return competing words to baseline accessibility, such that participants in the interference condition performed as if they had never seen the competitors prior to Phase 3.

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5 New-word naming time was included as a covariate in all analyses of RT data and was always a significant covariate.
Chapter 5 Study 2b

The data from Study 2a show that resolving interference between a target and a competitor involves suppressing the competitor, but does resolving interference also entail facilitating the accessibility of target words? That is, inhibitory and facilitative processes may operate simultaneously to resolve interference. In principle a system that simultaneously increased the accessibility of targets and decreased the accessibility of competitors could create an accessibility differential between targets and competitors more quickly, and thus resolve interference more efficiently, than a purely inhibitory system. Indeed, computational models of memory retrieval have successfully combined inhibitory processes that directly weaken competitors with facilitative processes that directly strengthen targets (e.g., Norman, Newman, & Detre, 2007). However, the possibility of cooperating facilitative and inhibitory processes has not been tested empirically. If facilitation does play a role in resolution, then successfully resolving interference should produce increased priming of target words, just as resolving interference produces decreased priming of competitors. I therefore tested 56 new participants (using the same selection criteria as in Study 2a) in the interference and baseline conditions. These participants were asked to name target words instead of competitor words in Phase 3. Except for the Phase 3 naming task, all other procedures (including data screening and trimming procedures) were the same as in Study 2a.

Results

The target words named in Phase 3 had been previously presented in Phase 1, and therefore should show some priming. Naming time for targets revealed this expected priming
relative to baseline (Figure 7b; see Table 4 for both target and new word naming times\(^6\)), \(F(1, 53) = 18.83, p < .001\). If targets had been facilitated during interference resolution in Phase 2 they should show a larger priming effect than words that had been presented during Phase 1 but had not taken part in a retrieval competition during Phase 2. To test for increased target priming, I compared the extent of priming for targets in the interference condition (which should reflect priming due to preexposure to these words during Phase 1, plus any facilitation due to competition resolution) with the amount of competitor priming in the no-conflict condition from Study 2a (which reflects only priming due to preexposure to the words during Phase 1). Target words in the interference condition showed 42 ms of priming (target naming time in the baseline condition – target naming time in the interference condition), no more than the 46 ms shown by competitors in the no-conflict condition (competitor naming time in the baseline condition – competitor naming time in the no-conflict condition). As a more rigorous test, I conducted a 2 (condition: baseline vs. priming) × 2 (word: target vs. competitor) ANCOVA with new-word naming time as a covariate. We would expect the ANCOVA to produce a significant interaction if interference resolution increases the amount of priming for targets. However, the interaction was not significant, \(F(1, 101) = 0.07, p > .70\), which suggests that resolving interference did not involve facilitating target words. Thus, contrary to models of interference resolution that include simultaneous inhibition and facilitation (Norman et al., 2007), interference in the present

\(^6\) Norms from the English Lexicon Project (Balota et al., 2007) confirm that the difference in baseline naming speed between targets and competitors is not limited to our study. As the focus of this study is the speed of naming relative to baseline (i.e., either priming or suppression) and not the absolute speed of naming, this difference does not affect our interpretation of the findings.
paradigm seems to be resolved by directly suppressing competitors without a corresponding facilitation of targets.

The data from Study 2b also allow us to test a possible alternative explanation of the slowed competitor naming observed in Study 2a. Specifically, it is possible is that the association between each target word and its competitor word was strengthened during the word-fragment-completion task in Phase 2. Thus, when a competitor was presented for naming in Phase 3, it may have triggered the retrieval of both the competitor and the target, slowing naming. However, if such association strengthening had occurred we would expect that both competitor and target naming would also be slowed. By contrast, we would not expect to observe any slowing of target-word naming if suppression was the source of the slowed competitor naming seen in Study 2a. Therefore, the finding from the current study that targets showed no slowing is inconsistent with an association-strengthening account of the competitor slowing observed in Study 2a.

Study 2 General Discussion

Direct evidence for the operation of inhibitory mechanisms at the behavioral level has been notoriously difficult to find (e.g., Macleod et al., 2003). In Studies 2a and 2b, I looked for a fingerprint of an inhibitory mechanism by measuring the consequences of interference resolution for the rejected competitor word. The results provide strong, direct evidence for an inhibitory mechanism in interference resolution: Participants who successfully resolved interference between competing words were subsequently slower to name the rejected word than participants who experienced no interference.

These studies are not the first to show that retrieving one piece of information has negative consequences for related information: Postretrieval deficits have been shown in a variety of paradigms, such as retrieving versus rereading recently presented information (Higgins & Johnson, 2009), fan-effect studies (Radvansky, Zacks, & Hasher, 2005), category-stem
completion (Blaxton & Neely, 1983), and the retrieval-induced forgetting (RIF) paradigm (M.C. Anderson, Bjork, & Bjork, 1994; M.C. Anderson & Spellman, 1995). However, many researchers have argued that these effects are best explained by mechanisms other than suppression (e.g., Gorfein & Brown, 2007; Higgins & Johnson, 2009; MacLeod et al., 2003). Perhaps the best existing evidence for suppression comes from RIF studies, in which participants learn lists of category-exemplar pairs and then practice retrieving a subset of these exemplars. This practice impairs subsequent retrieval of unpracticed exemplars. However, there have been reports of difficulty replicating some of the key findings supporting inhibitory explanations of RIF (e.g., Williams & Zacks, 2001), and several authors have proposed noninhibitory accounts of RIF effects (Macleod et al., 2003; Williams & Zacks, 2001). One way to adjudicate between inhibitory and noninhibitory accounts in general, however, is to search for converging evidence from different paradigms. The data presented here provide such evidence.

The present findings expand the current understanding of suppression effects in a number of ways. First, they show that suppression of competing words during retrieval occurs even in implicit tasks in which participants are not explicitly asked to retrieve a subset of previously learned information. Some RIF studies have found suppression effects using implicit tasks to measure suppression after explicit retrieval practice (e.g., Bajo, Gómez-Ariza, Fernandez, & Marful, 2006; Perfect, Moulin, Conway, & Perry, 2002). However, in the present studies, all phases—including encoding and retrieval—were implicit. Situations requiring explicit retrieval are common in laboratory and educational settings, but in everyday life much of memory retrieval is implicit – stimuli in the environment automatically cue multiple memories and suggest multiple possible responses and we are often aware only of the final retrieved memory. Therefore, implicit memory tasks may simulate an important aspect of the resolution of interference outside the laboratory. Second, the findings show that suppression of competing
information can occur even after a single retrieval episode, whereas most other studies have involved multiple retrieval attempts (though retrieval need not be successful; Storm & Nestojko, 2010), with a single attempt often producing no suppression (Shivde & Anderson, 2001) or even producing facilitation (Blaxton & Neely, 1983). Third, Study 2a provides information about the magnitude of suppression effects at retrieval, showing that interference resolution returns competing information to a baseline level of accessibility (but not lower). There was also no evidence of heightened accessibility (or activation) for target words, which is consistent with the view that the outcome of successful resolution of competition is heightened relative, and not absolute, accessibility of the target words.

The behavioral findings reported here are consistent with neuroimaging evidence that also suggests interference is resolved through suppression. For example, fMRI work shows that performance on a visual memory task is strongly related to individual (and age) differences in the reduction of activity in brain areas associated with processing of irrelevant material but not at all to activity in areas associated with processing of the to-be-remembered material (Gazzaley, Cooney, McEvoy et al., 2005; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Zanto & Gazzaley, 2009). There is also evidence, using an ERP index of the amount of information stored in working memory, that individuals with high working memory scores are distinguished from those with lower scores not by how much relevant information they encode into memory but by how much irrelevant information they hold in the focus of attention (McNab & Klingberg, 2008; Vogel, McCollough, & Machizawa, 2005). Consistent with inhibitory theory (Hasher et al., 1999), it has been suggested that an inhibitory mechanism filters out the irrelevant information (Awh & Vogel, 2008).

Effects similar to the suppression found here may occur in a variety of tasks, including complex working memory span tasks, which involve considerable levels of interference (e.g.,
Lustig et al., 2001), and which may require retrieval from long-term memory (e.g., Healey & Miyake, 2009; Unsworth & Engle, 2007). The present data are also relevant to neuroimaging findings that implicate the left inferior frontal gyrus (IFG) in interference-resolution processes (Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009; Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). On the basis of these studies, and assuming that degree of IFG activity indexes successful interference resolution which can be detected as slowing on a subsequent naming task, I predict that individuals showing the greatest IFG activity during interference resolution will also show the greatest slowing effect during a naming task.

Classic interference theory (e.g., Postman & Underwood, 1973) posits that memory failure is largely due to competition between memory traces at retrieval. This view of the centrality of interference has greatly influenced contemporary research, yet the critical question of how interference is resolved remains open and contested. Studies 2a and 2b provide some of the strongest evidence to date that retrieval of a memory trace entails the suppression of competing memory traces, reducing accessibility of these competitors to the baseline level of semantic memory. The logic of looking for the fingerprints of inhibition, not in what happens to target information, but in what happens to competing information, holds great promise for both behavioral and neuroimaging work.
Chapter 6 Aging and Interference Control

Older adults (age 60+) have difficulties with many foundational cognitive functions including working memory (Hasher et al., 2007; May et al., 1999), and explicit long-term memory (Grady & Craik, 2000; but see also Zacks & Hasher, 2006). Hasher and Zacks (1988) suggested that deficits in the ability to suppress might underlie these cognitive impairments. Indeed there is much evidence that older adults have great difficulty dealing with interference (and distraction in general). However, there is relatively little evidence linking this susceptibility to interference specifically to impaired suppression abilities (as opposed to some other mechanism of interference control). Here I use the paradigm introduced in Study 2 to test directly the hypothesis that older adults have impaired suppression abilities. Before presenting the findings, I briefly review the evidence supporting the distraction regulation theory of aging and memory (see Healey, Campbell, & Hasher, 2008 for a more extensive review).

There is a longstanding literature showing that older adults are more susceptible than younger adults to both proactive interference (Winocur & Moscovitch, 1993) and retroactive interference (Hulicka, 1967; See Kane and Hasher, 1995 for a review). More recent work has verified a causal link between interference and impaired memory in older adults by showing that manipulations that reduce the amount of interference in a memory task also reduce age differences in memory performance (e.g., Lustig et al., 2001; Rowe et al., 2008, Winocur & Moscovitch, 1983). For example, May et al. (1999) manipulated the impact of proactive interference on complex span performance by presenting the trials with the most to-be-remembered words, those that make the largest contribution to span performance, either at the end of the task (i.e., after considerable interference has built up) or the beginning of the task (i.e., before interference has built up). Older adults showed a large memory deficit relative to younger
adults in the high interference version of the task, but on the low interference version the age difference was dramatically reduced. The impact of distraction on the memory of older adults is not limited to proactive interference from previous trials.

Campbell, Hasher, and Thomas (2010) had participants perform a 1-back task on pairs of pictures and superimposed words before completing a paired associate learning task (picture-word pairs). Unknown to participants, the learning task included pairs that had been previously seen in the 1-back task (i.e., a picture paired with the same word it had been paired with in the 1-back task) as well as rearrangements of pairs from the 1-back task (i.e., a picture paired with the same word other than the one it had been paired with in the 1-back task). Older adults enjoyed a memory advantage for the intact pairs and suffered a disadvantage for the disrupted pairs, indicating that the previous, no longer relevant 1-back task was influencing their memory. By contrast the 1-back task had little impact on paired associate learning for younger adults. The Campbell et al. (2010) results show that, for older adults, the impact of distraction can extend across tasks.

The negative impact of distraction on older adult’s cognitive performance extends beyond memory tasks. Even with well-learned tasks such as reading, distraction has a disproportional impact on older adults. Connelly et al. (1991) used the reading with distraction task (see Study 1 here) in which participants had to read a short story with irrelevant text interspersed with the relevant text. They found that for control stories in which no distracting information was presented, older adults’ reading speeds were only slightly slower than younger adults’, but that for experimental stories which included distracting words and phrases related to the meaning of the relevant text, the older adults were disproportionately slowed. Distraction not only causes older adults to slow down, it also biases how they process task relevant information. Consider,
for example, the remote associates task (RAT: Mednick, 1962), which requires participants to find the word that links three weakly associated words (e.g., ‘space’, for the triplet “Ship, Outer, and Crawl”). If ostensibly unrelated distracting words are presented along with the word triplet (one for each word in the triplet, presented below the relevant word) younger adults generally ignore them, but older adults do not and their RAT performance either decreases or increases depending on whether the distracting words point away from or toward the correct solution (May, 1999; see Kim, Hasher, & Zacks, 2007 and Rowe, Valderrama, Hasher, & Lenartowicz, 2006 for related findings)

What is the mechanism that filters distracting information for younger adults but fails to do so for older adults? My coauthors and I have suggested that deficient suppression mechanisms are the culprit (Healey et al., 2008; Hasher et al., 2007). Unfortunately, just as much of the evidence supporting suppression as a mechanism of distraction control in general has been either indirect or highly controversial (see Study 2 above), much of the evidence for impaired suppression as the source of age related distraction control deficits has also been indirect. However, the novel method for detecting suppression effects I introduced in Study 2 allows for a more direct test of the hypothesis that older adults fail to suppress irrelevant information.
Chapter 7 Study 3a

Study 2a showed that in the course of resolving interference between a target word and a competing word, younger adults suppressed the competing word. This result confirmed a core prediction of inhibitory theory: that resolving interference entails reducing the accessibility of interfering information. Another core prediction of inhibitory theory, as it applies to age related deficits, is that older adults should show a reduced (or absent) suppression effect relative to younger adults. I tested this prediction by testing a sample of older adults as participants in exactly the same paradigm used in Study 2a.

Method

Participants, materials, and procedure

169 Older adults participated for monetary compensation. Older adults were recruited from a participant pool maintained by the Department of Psychology at the University of Toronto and were residents of Toronto, Ontario, Canada area. Participants (35 males) had an average age of 68.2 years \( (SD = 5.19) \) and had on average 16.4 years of education \( (SD = 3.45) \); education data was missing for 3 participants.

In all respects, other than the age of the participants, the study was identical to Study 2a. Rather than reproduce complete details of the method I provide only a brief overview (see Study 2a and especially Figure 6 for more detail). The paradigm consisted of 3 phases. In the critical interference condition, Phase 1 created the potential for interference by presenting a list of words for vowel counting that included pairs of orthographically similar words (e.g., allergy/analogy); Phase 2 encouraged interference resolution by asking participants to solve word fragments that resembled both words in a pair but could actually be completed only by the target word; Phase 3 sought evidence of suppression by having participants name the competitor words they should
have rejected in favor of the targets during Phase 2. In addition to the interference condition there were 3 control conditions. Participants in the no-resolution condition also saw targets and their competitors in Phase 1. This condition therefore created the potential for interference, but none of the word fragments in Phase 2 required participants to resolve that interference. Participants in the no-conflict condition solved word fragments for which they had seen only target words in Phase 1, and thus should have experienced little target-competitor interference. Participants in the baseline condition completed only Phase 3.

The same data trimming procedure employed in Study 2 was used here with one exception: older adults had a large number of extremely slow responses compared with younger adults and to reduce the impact of these outlying responses I applied a 15% winsorization to the data rather than the 5% used for younger adults. I note that 15% winsorization is more conservative than the 20% recommended by some statisticians (Erceg-Hurn & Mirosevich, 2008). I also note that using a 15% trim on the younger adult data does not change the pattern of results and that using a 5% trim on the older adult data does not change the qualitative pattern of results but adds variability making the effects difficult to detect statistically. Forty participants were excluded due to their reports of being aware that some words repeated across the phases of the study (cf. 37 for younger adults in Study 2a) and 8 participants were excluded for having fewer than 6 usable reaction times per condition leaving a final sample of 121.

Results and Discussion

To ensure that presenting both targets and competitors during Phase 1 succeeded in creating interference during Phase 2, I compared the competitor intrusion rate during fragment completion (i.e., producing the competitor rather than the target) in the interference condition, in which participants saw both the target and the competitor during Phase 1, with the intrusion rate
in the no-conflict condition, in which participants saw the target, but not the competitor, during Phase 1. As expected, older adults in the interference condition experienced interference, producing over twice as many intrusions ($M = 2.32, SEM = 0.28$) as older adults in the no-conflict condition ($M = 1.10, SEM = 0.25$), $t(60) = 3.10, p < .01$. I also examined overall fragment completion rates (i.e., solving the fragment with the correct target word). The no-resolution condition provides a baseline for fragment completion rates, as the fragments in this condition were unrelated to any words from Phase 1. No-resolution participants solved an average of $7.44 (SEM = 0.41)$ critical fragments. Participants in the no-conflict condition, who saw only targets in Phase 1, solved on average $9.28 (SEM = 0.42)$ critical fragments, reliability more than in the no-resolution condition, $t(63) = 3.09, p < .01$, confirming that pre-exposure to the target word facilitated fragment completion. Participants in the no interference condition, who saw both targets and their corresponding competitors in Phase 1, solved $9.00$ critical fragments on average ($SEM = 0.32$), significantly more than no-resolution participants, $t(65) = 2.93, p < .01$. Unexpectedly, and in contrast to the younger adult data from Study 2a, completion rates did not differ between the interference and no-conflict conditions, $t(58) = 0.53$. Moreover, the older adults and younger adults (i.e., comparing the results of Studies 2a and 3a) appear to have experienced similar levels of interference, as indicated by a non-significant age group by condition interaction on fragment completion rates, $F(2, 168) = 0.48, p = .62$.

The statistically equivalent fragment completion rates in the interference and no-conflict conditions and lack of an age effect raises the question of whether the experimental manipulation succeeded in producing interference for older adults, as it did for young adults in Study 2a. This is a critical issue as we would only expect suppression mechanisms to operate when interference occurs, therefore, determining if older adults have impaired suppression mechanisms requires that they actually experience interference. More specifically, to claim that older adults failed to
suppress competitors, I must first show that, in the interference condition, the competitors were actually competing with the targets during fragment completion. The intrusion rate data (i.e., that interference participants who were pre-exposed to both the target and competitor were more likely to intrude the competitor than no-conflict participants who were pre-exposed to only the target) clearly indicate that such competition was occurring. In contrast, overall fragment completion rates may provide a less sensitive test of interference: fragment completion rates are multiply determined (e.g., by vocabulary size, by verbal fluency) and it is possible that factors unrelated to interference resolution obscured the effect of interference. I return to these issues in the discussion section.

Naming times for competitors and new words are shown in Table 5 (see Figure 8a for a comparison with the younger adult data from Study 2). As with younger adults, there was no significant difference in new word naming time across conditions, $F(3, 117) = 1.89, p = .14$. However, visual inspection of the mean new word naming times suggests reasonably large fluctuations across conditions that could add error variance to the analyses of competitor naming times. I, therefore, included new word naming time as a covariate in all subsequent analyses.

In all conditions, except baseline, participants had seen the competitor words in an earlier phase before naming them, therefore in the absence of suppression we expect competitor naming to show priming relative to baseline. If older adults in the interference condition had suppressed competitors during interference resolution, they should show reduced or absent priming for competitors. However, older adults in the interference condition showed substantial priming for competitors, $F(1, 53) = 15.74, p < .001$. Older adults also showed priming in the no-resolution, $F(1, 58) = 13.54, p = .001$, and no-conflict, $F(1, 51) = 10.94, p = .002$, conditions. After controlling for new word naming time, there was no difference in competitor naming between.
the interference, no-resolution, and no-conflict conditions, $F(2, 92) = 0.52$, indicating that older adults showed equivalent priming across conditions. Comparing these results to the younger adult data from Study 2a (Figure 8a), the difference is stark: younger adults show clear evidence of suppression but older adults show no evidence of suppression. Confirming this interpretation, when older and younger adult data are combined, there is a significant age group by condition interaction effect on competitor word naming, $F(3, 212) = 3.48, p = .017$. These results provide a direct and powerful confirmation of the inhibitory theory of aging: older adults fail to suppress competitors during interference resolution.
Chapter 8 Study 3b

Study 3a showed that older adults did not suppress competitors during interference resolution. This finding raises the important question of what happens to target words during interference resolution for older adults. Study 2b showed that younger adults do not facilitate targets during interference resolution. But given the failure of older adults to suppress, it is possible that they compensate by facilitating targets. To test this possibility I replicated Study 2b with a sample of older adults.

Method

Participants, materials, and procedure

94 Older adults were recruited from the same pool and using the same procedure as in Study 3a. Participants (33 males) had an average age of 68.66 years ($SD = 4.99$) and had on average 16.69 years of education ($SD = 3.75$; education data was missing for one participant).

The study was identical to Study 2b in that interference and baseline conditions were run but rather than testing for competitor naming during Phase 3, target naming was tested. The same data trimming procedure used for Study 3a was used here.

Results and Discussion

Although target naming time in the interference condition was slightly faster than in the baseline condition, the effect did not reach significance, $F(1, 91) = 1.57, p = .214$ (Figure 8b; see Table 6 for both target and new word naming times). The fact that older adults showed no priming for targets clearly speaks against the hypothesis that older adults compensate for impaired suppression by facilitating targets but raises the paradoxical possibility that interference resolution actually reduced accessibility of targets. A clear way to determine if interference
resolution resulted in reduced target accessibility is to determine if the target priming effect (target naming time in the baseline condition – target naming time in the interference condition) is significantly different than the priming effect in a condition that reflects pure priming without any influence of interference. The no-conflict condition from Study 3a, in which participants are pre-exposed to words in Phase 1, name the same words in Phase 3, but resolve no interference in Phase 2, provides such an interference free priming baseline. Therefore, to test for reduced target priming I entered the interference condition from study 3b and the no-conflict condition from study 3a into a 2 (condition: baseline vs. priming condition) × 2 (word: target vs. competitor) ANCOVA with new-word naming time as a covariate. If interference resolution resulted in reduced priming this ANCOVA should yield a significant interaction (i.e., the priming effect should depend on whether targets or competitors are being named). However, the interaction was non-significant at the conventional alpha = .05 level, $F(1, 143) = 2.92, p = .09$, suggesting that target priming was neither significantly increased nor reduced as a result of interference resolution. I directly compared the older adult data with the younger adult data from Study 2 by combining the two data sets and rerunning the condition by word-type ANCOVA and added age group as an additional factor. If older and younger adults are processing targets differently during interference resolution, the 3-way interaction (age group x condition x word-type) should be significant, however, it was not, $F(1, 247) = 2.34, p = .13$, suggesting that older and younger adults are processing targets similarly. While it would be imprudent to dismiss completely the possibility that the trend toward reduced target priming for older adults reflects a true effect, it is clear that the present results provide little evidence for the hypothesis that older adults resolve interference by facilitating targets.
Study 3 General Discussion

The evidence reviewed in the introduction to Study 3 clearly indicates that older adults have difficulty controlling distraction and show great susceptibility to interference. However, until now there has been little direct evidence that this susceptibility to distraction is linked to impaired suppression abilities, as proposed by the Inhibitory Theory of aging. The finding that older adults did not suppress competitors during interference resolution (Study 3a) whereas younger adults did (Study 2a), provides some of the best direct support to date that older adults have impaired inhibitory mechanisms.

The fact that older adults neither suppress competitors (Study 3a) nor facilitate targets (Study 3b) raises the question of how they do resolve interference. As is clear from the solution rates from the fragment completion phase (see results section of Study 3a), older adults successfully produce the correct fragment solution on many trials, even in the interference condition. One possibility is that in the absence of suppression older adults rely on a deliberate post-retrieval checking procedure (e.g., they generate a candidate response, check if it fits the fragment, and if it does not they simply do not report it but also do not suppress it). Such a checking procedure may allow older adults to maintain accuracy on the fragment completion task despite an inability to suppress competitors. A clear disadvantage of such a process is that it is task specific whereas the same suppression process can presumably be applied across a variety of tasks. The proposal that older adults compensate for impaired suppression abilities by employing task specific post-retrieval strategies, leads to the prediction that older adults’ performance on high interference tasks should depend on how amenable the task is to non-suppression based strategies. For example, fragment completion presents a clear cue, the fragment, that can be unambiguously checked against candidate responses retrieved from both
implicit memory and semantic memory. In contrast, in explicit retrieval tasks, such as complex span, there is no explicitly provided cue that can be uniquely matched to a particular memory.

Together Studies 2 and 3 provide strong preliminary evidence that younger adults suppress competition during interference resolution but older adults do not, but they also raise an important question: While older adults did experience interference in Study 3, as indicated by intrusion rates during fragment completion, contrary to previous work they did not appear to experience any more interference than younger adults. For example, using the same materials and a design closely resembling the first two phases of Studies 2 and 3, Ikier et al. (2008) found that older adults showed a greater interference effect than younger adults when solving fragments for which they have been pre-exposed to both the target and a competitor. One potentially critical difference between the studies is that whereas the current studies used a between-subjects design, the Ikier et al. study used a within-subjects design wherein each participant had been pre-exposed to both targets and competitors for some fragments but to only targets for other fragments. That is, in the current study all the critical fragments a particular participant encountered were either hi-interference (for interference condition participants) or lo-interference (for no-conflict and no-resolution participants), but in the Ikier et al. study each participant experienced both hi-interference and lo-interference fragments. It is possible that older adults have less difficulty dealing with distraction when most of the trials are hi-interference (e.g., if interference is frequent they may be more likely to adopt post-retrieval checking strategies as discussed above). An important extension of the present work will be to test for suppression effects (or lack thereof) in a paradigm on which older adults show a greater interference effect than younger adults.
Chapter 9 General Discussion and Concluding Remarks

Limitations on memory have long interested psychologists. The environment constantly presents us with massive amounts of information and it is far beyond our ability to actively process all of it and carefully consider all possible responses. However, to accomplish our goals we must process at least some of this information and decide upon an appropriate response. Therefore, one of the primary obstacles to successful information processing and interaction with the environment is winnowing the relevant from the irrelevant, the appropriate from the inappropriate. Here I have argued that this obstacle is overcome by using attention to actively inhibit information that is currently irrelevant. That is, inhibitory processes are used to narrow the scope of information processing and the resulting overt responses by excluding information and responses that are situationally inappropriate (for a more detailed exposition of this view, see Hasher and Zacks, 1988; Hasher et al., 1999, 2007). This framework suggests that interference and distraction should be a powerful determinant of cognitive performance across a wide variety of tasks, and that individual, and group, differences in the ability to regulate interference should be strongly predictive of how well an individual will do on a particular task. While many existing findings support this framework (see Healey et al., 2008 and Hasher et al., 2007 for recent reviews), the studies reported here directly test several critical predictions which have not yet been empirically confirmed.

Study 1 used structural equation modeling to explore the relationships between working memory tasks, long-term memory tasks, and fluid intelligence. Supporting previous work (Mogle et al. 2008; Unsworth et al. 2009), working memory and long-term memory tasks were highly correlated and both accounted for substantial variance in fluid intelligence. The novel, and important finding from Study 1 was that interference control tasks mediated the relationship
between the memory tasks (both working and long-term memory) and fluid intelligence. The results of Study 1 indicate that the ability to control interference plays a major role in memory and cognition in general. The results, however, shed little light on precisely how interference is controlled. The nature of these mechanisms was investigated in Study 2.

Using a novel paradigm in Study 2, I showed that, for younger adults, resolving interference between target and competing information entailed suppressing, or inhibiting, the competing information (but not facilitating target information). These results provide some of the most direct evidence available that interference is regulated through suppression. Study 3 leveraged the paradigm introduced in Study 2 to test and confirm an important prediction of the inhibitory theory of cognitive aging: that older adults are less able to suppress competing information during interference resolution than are younger adults. Together these three studies expand our understanding of why memory is limited, how that limitation changes over the lifespan, and the impact of memory limits on other aspects of cognitive functioning.

Relation to existing work

Much of the existing work on the role of memory in fluid intelligence has been inspired by the original Baddeley and Hitch (1974; Baddeley, 2000) working memory model and more recently, by models based on the notion of a focus of attention (e.g., the similar, but not identical, models of Cowan, 2005 and Oberauer, 2002). The Baddeley and Hitch model emphasizes active maintenance of information in domain specific storage systems, with a central executive to control the flow and processing of the information. Focus of attention models (Cowan, 2005; Oberauer, 2002) propose the focal elements of working memory are held in an accessible state by a highly capacity limited attentional system. None of these models explicitly includes inhibitory interference control mechanisms, yet the present data suggest such mechanisms
explain much of the relationship between working memory and fluid intelligence. It remains to be seen whether this apparent conflict is best resolved by modifying existing working memory models to include interference control mechanisms, or by a model wherein inhibitory mechanisms control the flow of information into and out of a single memory system.

The inhibitory framework outlined here is closely related to the executive attention view of Kane, Engle, and colleagues (e.g., Kane et al., 2007). Both views emphasize the importance of interference and need to use attentional mechanisms to overcome interference. However, while the executive attention view does allow for inhibitory mechanisms, it explicitly argues that any individual differences in inhibitory ability result from variations in an ability to control attention in general (Kane et al., 2007; Conway et al., 1999; Conway & Engle, 1994). That is, the executive attention view holds that variations in working memory capacity produce variations in inhibitory ability. The similarity of the two frameworks has made it difficult to distinguish them based on existing data. However, whereas the executive attention view would predict that working memory should mediate any relationship between interference control and fluid intelligence, the inhibitory view predicts the opposite: that inhibitory control should mediate the working memory/fluid intelligence relationship. Therefore the findings from Study 1, that interference control mediates the complex span/fluid intelligence relationship, are inconsistent with the controlled attention view and instead support inhibitory theory.

Work on the neural underpinnings of interference control, and age differences in interference susceptibility, may be relevant to understanding the relationship among interference control, memory retrieval, and fluid intelligence. A growing body of research links interference-resolution in tasks conceptually similar to the fragment completion task used here to activity in left inferior frontal gyrus (Nelson, Reuter-Lorenz, Persson, Sylvester, & Jonides, 2009; Thompson-Schill, D’Esposito, Aguirre, & Farah, 1997). For example, Jonides et al. (2000) used
the recent negatives task. On each trial of the task, participants are given a small set of items to remember followed by a probe item; a positive response is required if the probe was a member of the current set, if the probe was not a member of the current set, a negative response is required even if the probe was a member of a previous set. For younger adults, reaction times were slower on such recent negative trials, which require giving a negative response to a stimulus that had been part of the memory set on a recent but non-current trial, than on non-recent negative trials on which the probe was not a member of any recent set. This interference related slowing was associated with increased activity in the left inferior frontal gyrus (Brodmann’s area 45). Older adults showed even greater slowing to recent negatives relative to non-recent negative trials and showed less activation in the same left lateral prefrontal area. These results suggest that older adults’ inability to ignore currently irrelevant information (in this case the familiarity of previous trial items) is related to decreased activation in the prefrontal cortex areas believed to be responsible for distraction control.

Considering this evidence on the neural underpinnings of interference control, together with the behavioral results of Study 3, leads to the prediction that older adults performing the fragment completion interference control task used in Studies 2 and 3 should show less activity in the relevant prefrontal areas than younger adults. Furthermore, the degree of activity in interference control areas of the brain during the fragment completion phase of the task should be a very strong predictor of the strength of the suppression effect during the final naming phase, both for older and younger adults. A further prediction is that if, as I have argued, interference control ability is strongly related to fluid intelligence, then brain areas responsible for interference resolution should show activity during fluid intelligence tasks. One potential problem is that there is little evidence linking left inferior frontal gyrus activity with performance on fluid intelligence tasks (in contrast, considerable evidence links other prefrontal areas to fluid
Further evidence of the neural correlates of distractibility comes from a study by Gazzaley, Cooney, Rissman, and D'Esposito (2005). They presented participants with a series of faces and scenes (e.g., a sunset). In one condition participants were told to ignore the faces and remember the scenes, in another condition they were told to remember the faces and ignore the scenes. Gazzaley, Cooney, Rissman, and D'Esposito found that when they were told to remember the scenes and ignore the faces, both older and younger adults showed increased activity in the parahippocampal place area (PPA), a region known to be involved in the processing of scenes, relative to a control condition in which participants passively viewed the pictures. In contrast, when told to ignore the scenes, activity in the PPA decreased below baseline, but only for younger adults: older adults did not show decreased activity when scenes were irrelevant. That is, when scenes were relevant, there were no age differences in PPA activity but when scenes were irrelevant, younger adults suppressed PPA activity but older adults did not. Moreover, the extent to which activity in the PPA was suppressed when remembering faces, predicted memory accuracy. Thus, one neural signature of older adults’ distractibility appears to be activity in processing areas that fails to discriminate between relevant and irrelevant information. It should be noted that, the Gazzaley et al. studies involve interference resolution at encoding, in contrast, the paradigm used in Studies 2 and 3 involves suppression at retrieval. I return to the issue of distraction at encoding versus at retrieval below.

Outstanding questions and future directions

Study 1 clearly showed that interference control accounted for a large proportion of the variance in fluid intelligence. However, an appreciable portion remained unexplained. It is possible that the unexplained variability is due to less than perfect reliability of the tasks used to
measure the constructs (correlations are limited by reliability). It is, however, quite possible that
cognitive processes other than interference control make an important contribution to fluid
intelligence. Just as interference control explained much, but not all of the variation in fluid
intelligence, it explained much, but not all of the relationship between long-term memory and
fluid intelligence. This less than perfect mediation leaves open the possibility that memory
processes other than interference control contribute to fluid intelligence. For example, some have
argued that a general ability to control attention (rather than to control interference in particular)
underlies much variation in cognitive ability (Kane et al., 2007), while others have argued that
the ability to form arbitrary bindings between items in memory is critical (Oberauer, 2005; but
see Campbell et al., 2010 for evidence of intact binding in older adults), still others argue that the
ability to allocate domain general resources efficiently between multiple sub-tasks is central
(Towse et al., 1998). Most studies in the literature, including the present Study 1, investigate
only one of these theories at a time. A large-scale study that included tasks measuring as many of
these putative cognitive primitives as possible would be a major contribution to the field.

Study 1 showed that individual differences in interference control explains much of the
relationship between memory and fluid intelligence - for young adults. Whether the same pattern
holds for older adults is an important question. Given the finding from Study 3 that older adults
fail to suppress competitors during interference resolution, they may show a different pattern of
correlations between interference control ability and fluid intelligence than younger adults. If
older adults compensate for impaired suppression abilities by relying on other processes to
resolve interference, it is likely that the predictive utility of interference control would decrease
with age, perhaps mirrored by an increase in the predictive utility of whatever other processes
compensate for impaired suppression. Addressing these issues will require a combination of
experimental work to identify which processes compensate for impaired suppression and correlational work to explore individual differences.

Study 2 provides strong evidence that resolving interference between orthographically similar items in an implicit memory task entails suppressing competing information. While these results make a major contribution to a longstanding debate, they leave several important questions for future work. For example, do the same sort of suppression mechanisms found for orthographic interference resolution subserve resolution of other types of interference (e.g., between semantically similar items). And does interference resolution in explicit memory tasks also involve suppression? While the primary focus of the current dissertation has been interference in memory, interference does not occur only in memory tasks. How is interference resolved when the distracting information is perceptually present (e.g., as in the reading with distraction task)? I would suggest that similar mechanisms resolve interference regardless of whether the interfering information is perceptually present or stored in memory. Moreover, I would predict that individual differences in perceptual interference control should be highly related to individual differences in memory interference control. These claims are supported by the fact both perceptual and memory based interference tasks loaded onto a single interference control latent variable in Study 1 and that this latent variable predicted fluid intelligence.

However, a deeper exploration of the similarities and differences of resolving different types of interference promises to be a productive avenue for future research.

Finally, it will be important to explore individual differences in the suppression effect identified in study 2. A clear prediction of inhibitory theory is that people with the best performance on memory tasks should show the largest suppression effects. Moreover, insofar as the suppression effect measures the efficiency of inhibitory processes, individual differences in
the effect should powerfully mediate the relationship between memory tasks and fluid intelligence. Such individual difference work will require modifying the existing paradigm to provide a psychometrically reliable and valid measure of an individual’s suppression ability.

Conclusion

Within the individual difference literature the importance of memory, particularly memory over the short-term, for ‘higher order’ cognitive functions, or fluid intelligence has long been recognized. However, identifying which aspects of memory are most important in this respect has been difficult. Within the long-term memory literature the powerful role of interference in determining memory performance has long been known, but identifying the mechanisms by which interference is controlled remains a challenge. In this dissertation I have tried to address both of these outstanding questions and at the same time bridge a gap between these two literatures (individual differences and long-term memory) which until recently have had relatively little contact. The results show that the ability to control interference makes a major contribution not just to memory, but also to fluid intelligence and that suppression of competing information is an important mechanism of interference control.
References


Naveh-Benjamin, M., & Guez, J. (2000). Effects of divided attention on encoding and retrieval


Table 1

Simple Correlations and Descriptive Statistics

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<td>7. Operation Span</td>
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<td>.380</td>
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<td>.175</td>
<td>.264</td>
<td>.122</td>
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Mean                     | 0.73 | 21.49 | 0.09 | 0.66 | 53.19 | 0.58 | 23.58 | 21.63 | 19.36 | 9.28 | 14.45 | 11.05 |
SD                       | 0.16 | 10.04 | 0.14 | 0.14 | 22.77 | 0.26 | 4.61  | 5.36  | 3.46  | 2.88 | 2.10  | 2.40  |
Reliability              | 0.68 | 0.82  | 0.77 | 0.77 | 0.96  | 0.65 | 0.72  | 0.77  | 0.51  | 0.70 | 0.78  | 0.69  |
Skew                     | 0.19 | 0.01  | -2.03 | 0.17 | -0.14 | -0.17 | -0.09 | -0.22 | -0.04 | -0.37 | 0.27  | 0.15  |
Kurtosis                 | 0.53 | 0.45  | 3.72 | -0.32 | 0.30  | -0.89 | -0.51 | 0.08  | -0.84 | 0.05 | -0.98 | 0.88  |
Transformation           | Asin | Sqrt  | Log  | Sqrt | -     | -     | -     | -     | -     | -    | -     | -     |

Note: Correlation coefficients in bold are significant at the .05 level. Means, SDs, and reliabilities were calculated before transformations. Correlations, skew, and kurtosis were calculated after transformations. To calculate reliability for N-Back and Directed Forgetting we computed three tasks scores for each participant, each based on a third of the trials (e.g., trial 1 would contribute to score 1, trial 2 to score 2, trial 3 to score 3, trial 4 to score 1, etc.) and then calculated Cronbach’s alpha based on the three scores. For all other tasks, Cronbach’s alpha was calculated based on all items from the task (i.e., each trial in the span tasks; each problem in the gF tasks). Asin = Arcsine; Sqrt = Square Root.
Table 2

Fit Indices for Models Reported in Study 1.

<table>
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<tr>
<th>Model</th>
<th>df</th>
<th>$\chi^2$</th>
<th>$\chi^2/df$</th>
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<th>NNFI</th>
<th>CFI</th>
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<td>.93</td>
<td>.95</td>
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<td>32.07</td>
<td>1.34</td>
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<td>Span-gF Path Constrained to Zero</td>
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<td>32.20</td>
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Note: The section for each figure provides the fit indices for the model depicted in the figure (bolded line) and any alternate models considered. See text for details on the alternate models and descriptions of the fit indices. For all $\chi^2, p > .05$. gF = fluid intelligence; LTM = Long-term memory.
Table 3

Mean Reaction Times (in Milliseconds) in the Phase 3 Naming Task in Study 2a.

<table>
<thead>
<tr>
<th>Word Type</th>
<th>Interference $n = 26$</th>
<th>No-Resolution $n = 24$</th>
<th>No-Conflict $n = 28$</th>
<th>Baseline $n = 22$</th>
</tr>
</thead>
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<tr>
<td>Competitor</td>
<td>610 (15.7)</td>
<td>577 (15.8)</td>
<td>569 (15.8)</td>
<td>615 (17.7)</td>
</tr>
<tr>
<td>New</td>
<td>576 (13.2)</td>
<td>567 (13.6)</td>
<td>563 (14.3)</td>
<td>576 (15.1)</td>
</tr>
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Note: Values in parentheses are standard errors of the mean.
Table 4

Mean Reaction Times (in Milliseconds) in the Phase 3 Naming Task in Study 2b.

<table>
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<th>Word Type</th>
<th>Interference</th>
<th>Baseline</th>
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<td></td>
<td>$n = 30$</td>
<td>$n = 26$</td>
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<tr>
<td>Target</td>
<td>506 (13.7)</td>
<td>548 (17.6)</td>
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<tr>
<td>New</td>
<td>543 (18.5)</td>
<td>547 (18.9)</td>
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Note: Values in parentheses are standard errors of the mean.
Table 5

Mean Reaction Times (in Milliseconds) in the Phase 3 Naming Task in Study 3a.

<table>
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<th>Word Type</th>
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<td>$n = 25$</td>
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Note: Values in parentheses are standard errors of the mean.
Table 6

Mean Reaction Times (in Milliseconds) in the Phase 3 Naming Task in Study 3b.

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<th>Word Type</th>
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<td>$n = 27$</td>
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<td>Target</td>
<td>574 (12.5)</td>
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<td>New</td>
<td>583 (11.0)</td>
<td>599 (8.2)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses are standard errors of the mean.
Figure 1. A confirmatory factor analysis with all four constructs. The rectangular boxes represent the observed variables (i.e., task scores) the ovals represent the latent variables. The numbers next to the single-headed arrows connecting the observed and latent variables are the standardized factor loadings of the particular task. The numbers on the left hand side of the observed variables represent the error variance for the associated variable. The curved arrows representing correlations between the latent variables and the numbers next to these arrows can be interpreted as correlation coefficients. All Paths are significant at the .05 level. LTM = long-term memory; gF = fluid intelligence.
Figure 2. A structural equation model testing for mediation of the complex span/fluid intelligence relationship by long-term memory. The single-headed arrows connecting latent variables represent hypothesized direct effects of one variable on another; the numbers next to single-headed arrows are standardized path coefficients and can be interpreted as standardized regression coefficients. For this and all subsequent figures, observed variables and the corresponding factor loadings are omitted. In all cases, the values and pattern of loadings were similar to the corresponding values show in Figure 1. Solid paths are significant at the .05 level, dotted paths are non-significant. LTM = long-term memory; gF = fluid intelligence.
Figure 3. A structural equation model testing for mediation of the complex span/fluid intelligence relationship by interference control. Solid paths are significant at the .05 level, dotted paths are non-significant. gF = fluid intelligence.
Figure 4. Structural model showing the proposed relationships among complex span, long-term memory, interference control, and fluid intelligence. Solid paths are significant at the .05 level, dotted paths are non-significant. LTM = long-term memory; gF = fluid intelligence.
Figure 5. A structural equation model testing for mediation of the LTM/fluid intelligence relationship by interference control. Solid paths are significant at the .05 level, dotted paths are non-significant. gF = fluid intelligence.
Figure 6. Comparison of the sequence of events in the four conditions used in Studies 2 and 3 (interference, no-resolution, no-conflict, and baseline). The top row shows examples of competitor items (e.g., allergy) and target items (e.g., analogy). Note that all items were presented individually and competitor items were always presented before target items in Phase 1 (see text). The middle row shows examples of the word fragments to be solved in Phase 2, along with their solutions. The bottom row shows examples of the critical words named in Phase 3.
Figure 7. Panel A: Mean competitor naming time by condition in the Phase 3 naming time task of Study 2a. Panel B: Mean target naming time by condition in the Phase 3 naming task of study 2b. Error bars represent one standard error of the mean.
Figure 8. Panel A: Mean competitor naming time by condition in the Phase 3 naming time task for older versus younger adults (Studies 2a/3a). Panel B: Mean target naming time in the Phase 3 naming task for older versus younger adults (Studies 2b/3b). Error bars represent one standard error of the mean.
Appendix

Target/competitor pairs used in Studies 2 and 3 along with corresponding fragments.

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<tr>
<th>Fragment</th>
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