Working Memory Capacity and Fluid Intelligence: Maintenance and Disengagement

Zach Shipstead[1], Tyler L. Harrison[2], and Randall W. Engle[2]

[1]Department of Social and Behavior Sciences, Arizona State University; and [2]Attention and Working Memory Lab, Georgia Institute of Technology

Abstract

Working memory capacity and fluid intelligence have been demonstrated to be strongly correlated traits. Typically, high working memory capacity is believed to facilitate reasoning through accurate maintenance of relevant information. In this article, we present a proposal reframing this issue, such that tests of working memory capacity and fluid intelligence are seen as measuring complementary processes that facilitate complex cognition. Respectively, these are the ability to maintain access to critical information and the ability to disengage from or block outdated information. In the realm of problem solving, high working memory capacity allows a person to represent and maintain a problem accurately and stably, so that hypothesis testing can be conducted. However, as hypotheses are disproven or become untenable, disengaging from outdated problem solving attempts becomes important so that new hypotheses can be generated and tested. From this perspective, the strong correlation between working memory capacity and fluid intelligence is due not to one ability having a causal influence on the other but to separate attention-demanding mental functions that can be contrary to one another but are organized around top-down processing goals.

The scientific study of intelligence can be traced to Charles Spearman in the early 1900s and his concept of general intelligence (Spearman, 1925). In simple terms, performance on all cognitive tasks is positively correlated and seems to stem from a single cognitive factor. Although general intelligence has proven to be a meaningful concept (Hunter & Schmidt, 2004), modern thinking and research largely have been influenced by the perspectives of Donald O. Hebb and Raymond Cattell who introduced a distinction between general crystalized intelligence and general fluid intelligence (Cattell, 1943; Hebb, 1941a, 1941b). *Crystalized intelligence* refers to the ability to put learned knowledge to use, with vocabulary being a classic example. *Fluid intelligence*, on which this article largely focuses, refers to the ability to reason through and solve novel problems.

As influential as these ideas have been, factors such as fluid intelligence are largely statistical concepts with little more than glib descriptions of the underlying psychological mechanisms. To have any hope of achieving a true understanding of the nature of human intelligence, researchers need to build better understanding of the mechanisms underlying these concepts.

Working Memory Capacity as a Determinant of Fluid Intelligence

One manner in which researchers attempt to understand fluid intelligence mechanistically is through study of working memory capacity. Working memory is a cognitive system that allows people to temporarily maintain information in a highly accessible state (Baddeley, 1986; Cowan, 1988). When referring to its "capacity," researchers are speaking of differences people show in the functionality of this system (e.g., differences in fixed storage capacity or aptitude for focusing attention). Indeed, working memory capacity does appear to be a critical

Corresponding Author:
Zach Shipstead, Department of Psychology, Alma College, Alma, MI, 48801.
E-mail: shipsteadzm@alma.edu

component of fluid intelligence. Investigators routinely find that individual differences in working memory capacity account for at least half (Kane, Hambrick, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Süß, 2005) of the differences people show in fluid intelligence, and they sometimes find a nearly perfect correlation (Chuderski, 2013).

The common sentiment regarding the strong correlation between working memory capacity and fluid intelligence is clearly laid out in the following quotations. In short, working memory is believed to provide a system in which problems can be represented. In turn, the stability of these representations facilitates problem solving ability:

> We think that what is common to all reasoning tasks is the fact that their solutions require the construction of new structural representations. . . . The complexity of the new structures is limited by the capacity of working memory. (Oberauer, Süß, Wilhem, & Sander, 2007)

> [T]he crucial cognitive mechanism underlying fluid ability lies in storage capacity, which enables people to actively maintain distinct chunks of information and flexibly construct task-relevant bindings among them. (Chuderski, Taraday, Nęcka, & Smoleń, 2012)

> The [working memory] processes that allow appropriate information to enter the focus of attention clearly make the stronger contribution to higher-order cognition. (Shipstead, Redick, Hicks, & Engle, 2012)

> It is only in fairly recent years, relative to the age of the field, that so-called "working memory" has come to be viewed as a key determiner of fluid intelligence. (Sternberg, 2008)

One need only look to the field of working memory training to see just how pervasive this thinking is. Many studies on working memory training are conducted with the expressed goal of increasing fluid intelligence by strengthening working memory (Jaeggi, Buschkuehl, Jonidas, & Perrig, 2008; Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Redick et al., 2013). The concept of working memory capacity as a determinant of fluid intelligence is so well accepted that much of the training literature relies on increases in fluid intelligence (or lack thereof) as a criterion for judging the efficacy of interventions (Au et al., 2015; Melby-Lervåg & Hulme, 2012) and whether this is even a reasonable expectation rarely is questioned (but see Harrison et al., 2013). Most critiques of working memory training have neglected to so much as raise the possibility that working memory capacity is anything but

a direct influence on fluid intelligence (e.g., Morrison & Chein, 2011; Shipstead, Redick, & Engle, 2010, 2012; Sternberg, 2008).

Yet, in considering the belief that working memory capacity is the major determinant of a person's fluid intelligence, it is important to remember that most data regarding the relation between working memory and fluid intelligence have been collected via correlational research. In reality, empirical evidence for a system in which working memory feeds information to reasoning processes is lacking (Harrison et al., 2013). The researchers in most studies in this literature would be equally accurate if they argued that people with high fluid intelligence are better at generating strategies that allow for superior performance on tests on working memory capacity (e.g., Salthouse & Pink, 2008).

Of course, it is reasonable to assume that the act of solving a fluid intelligence problem requires some form of mental representation, and working memory seems as plausible a source as any. Yet, this perspective is more of a starting point than a conclusion, and we see several reasons that the relation should be considered more broadly.

First, the traditional view does not clarify the nature of human reasoning so much as it states a belief that mental representations are a prerequisite for reasoning. Second, it assumes that studying working memory capacity enhances the understanding of fluid intelligence but not the converse. It treats working memory capacity as something concrete and elemental, while fluid intelligence remains a divine outcome. Finally, maintenance-centered perspectives paint a somewhat static picture of the common ground between working memory capacity and fluid intelligence. As a result, the dynamic nature of reasoning is ignored.

Building off of this final point, we note that the ability to maintain representations is only one half of the problem-solving-equation. Initial hypotheses regarding the solution to a problem can be wrong. Failure to update these hypotheses in response to new data result in fixation on outdated ideas (DeCaro, Van Stockum, & Wieth, 2015). To understand the relation of working memory capacity to fluid intelligence, researchers need to develop theories that focus on factors beyond maintenance capacity. In particular, we argue that the ability to disengage from outdated information is equally critical to our understanding complex cognition.

A New Perspective of the System Underlying Working Memory Capacity and Fluid Intelligence

In contrast to the traditional perspective in which working memory capacity and fluid intelligence represent distinct (but related) cognitive systems, our view is that
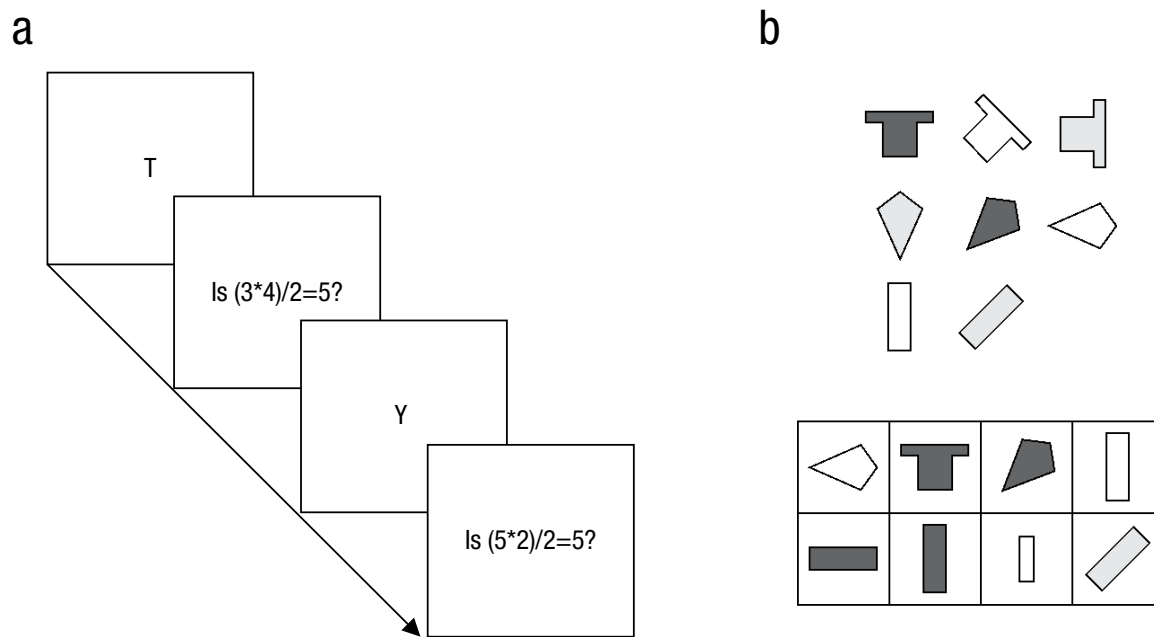
Fig. 1. Illustrations of an operation span task and a prototypical fluid intelligence task. (a) Sequence of events that occur in the operation span task. The letters must be remembered; the mathematical equations must be verified. (b) Prototypical fluid intelligence task. Test takers see a 3 × 3 array of items, in which one item is missing. They need to select which, of several, options completes the sequence.

these abilities have their origin in a single top-down executive attention system (Engle, 2002; but see Ackerman, Beier, & Boyle, 2005). This is not to say that working memory capacity and fluid intelligence are the exact same construct (e.g., Kyllonen & Christal, 1990). The point we are building toward is one in which working memory capacity and fluid intelligence arise from similar cognitive mechanisms but are reliant on these mechanisms to different degrees.

Yet, when examining tasks used to measure working memory capacity and fluid intelligence, one finds that the traditional perspective has a certain intuitive appeal. Figure 1a presents a prototypical measure of working memory capacity, known as the operation span task. This style of memory test is more broadly known as the *complex span* task (Daneman & Carpenter, 1980; Turner & Engle, 1989). In complex span tasks, a list of to-be-remembered items (the letters) is shown, such that item presentation is interrupted by a to-be-solved processing task (the mathematical operations). People who have relatively good memory for the to-be-remembered items are classed as having "high working memory capacity." People with relatively poor memory are classed as having "low working memory capacity."

Figure 1b presents a reasoning task that is similar to Raven's Progressive Matrices (Raven, 1990), which is the prototypical measure of fluid intelligence. In this task, information is presented in a 3 × 3 grid, with one item missing. The test taker's job is to decide which of several options belongs in the blank space. The context of these novel problem-solving tasks gives rise to the classic definition of fluid intelligence as the ability to reason with new (sometimes abstract) information, as opposed to reasoning with domain-specific, previously acquired, knowledge (Ackerman, 2000; Carroll, 1993; Horn, 1968; Horn & Cattell, 1966). The more of these puzzles a person can solve within a given time period (typically varying between 10–45 min), the higher that person's fluid intelligence is assumed to be.

The input and output demands for these tasks are quite different, which makes it easy to draw a conceptual distinction between working memory capacity (temporary memory) and fluid intelligence (reasoning with new information). However, investigators in numerous studies have found near-perfect and even perfect correlations between working memory capacity and fluid intelligence (e.g., Chuderski, 2013; Colom, Rebolloa, Palaciosa, Juan-Espinosa, & Kyllonen, 2004; Oberauer et al., 2005; Shipstead, Lindsey, Marshall, & Engle, 2014). This suggests that the cognitive processing that occurs between input and output is more similar than the surface features of the tasks would suggest. Although it is easy to draw a conceptual distinction between working memory capacity and fluid intelligence, in practice they simply are not that different.

Figure 2 outlines our conceptualization of the underlying system. Note that neither working memory capacity
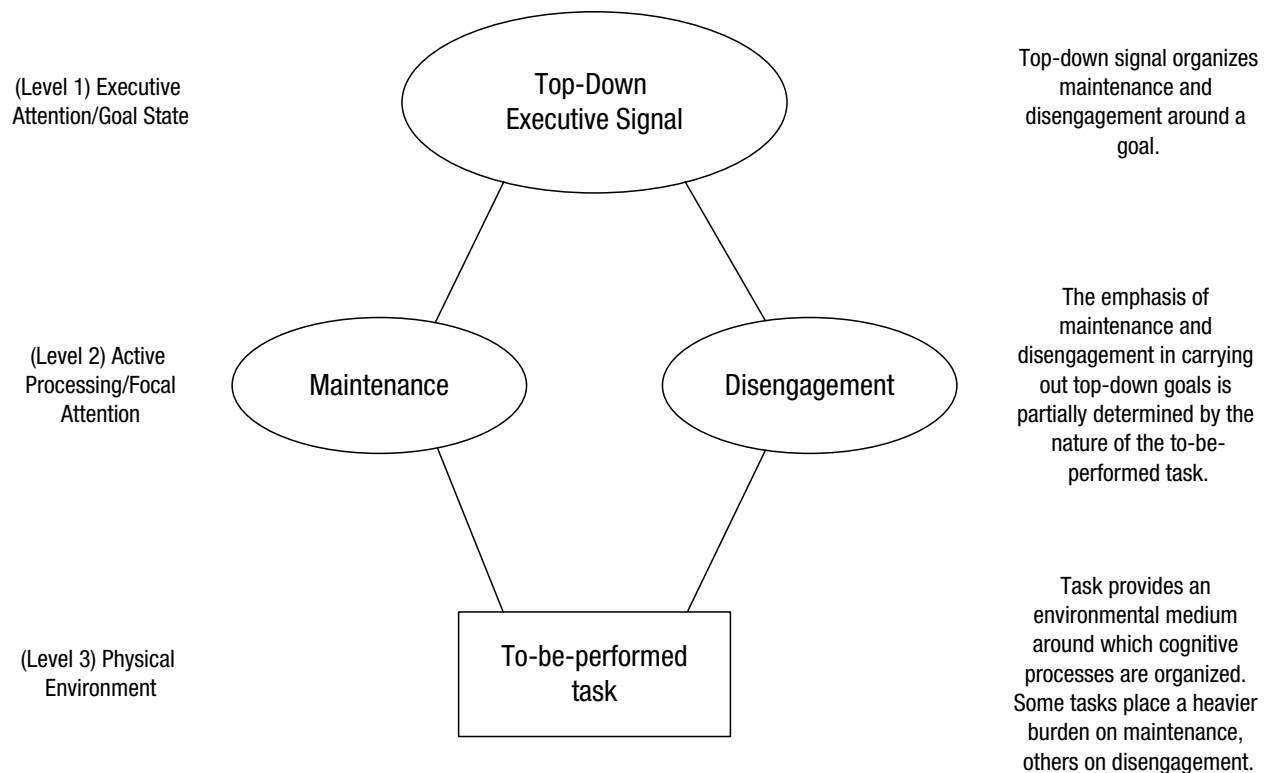
Fig. 2. The present perspective of complex cognitive abilities.

nor fluid intelligence is explicitly named as a component of the model. With regard to mental abilities, the distinction we draw between working memory capacity and fluid intelligence has little to do with hard-wired structures (e.g., memory structure; Atkinson & Shiffrin, 1968). Instead, it is a matter of how much emphasis tests of each cognitive ability place on acts of maintenance and acts of disengagement.

Before unpacking this statement, we need to reinforce a recurring theme: the distinction between tests and the abilities that drive test performance. Experimental psychology is largely concerned with operational definitions—tests that ostensibly require certain mental processes. The operation span and Raven task (Fig. 1) are relevant examples. Our focus, however, is on the mental processes that account for the correlations amongst several operational definitions.

In the model, Level 3 represents a test someone might be given. Levels 1 and 2 are cognitive processes that might be reflected in test performance. Tests of working memory capacity and tests fluid intelligence exist at Level 3. One cannot confuse them with the cognitive processes that they measure. The goal of complex cognition is to complete complex tasks. Tests of working memory capacity and of fluid intelligence are simply examples of such tasks on which cognitive processes function.

To further break down Figure 2, we note that the fundamental component of complex cognition is top-down executive attention (Level 1). Stated simply, executive attention represents the ability to organize processing around objectives (see work in brain science relevant to this issue; e.g., Miller & Cohen, 2001; Norman & Shallice, 1986; O'Reilly, Braver, & Cohen, 1999; Posner & DiGirolamo, 1998). People who can organize cognition in a goal-relevant manner do well on many types of task (e.g., positive manifold; Spearman, 1904). People who cannot organize cognition in a goal-relevant manner struggle on many types of task. In extreme cases, this disorganization may take the form of disorders such as schizophrenia (Cohen, Braver, & O'Reilly, 1996) or deficits of attention (Diamond, 2005).

In our model, executive attention is deployed via two broadly defined mechanisms (Level 2). It is at this point that working memory capacity and fluid intelligence become distinguishable constructs. The first mechanism is intentional *maintenance*. The act of focusing attention reduces the likelihood that relevant information will be lost due to interference (e.g., Cowan, 2001; Oberauer et al., 2007). The second mechanism is intentional *disengagement*.[1] Removing irrelevant information from active processing also reduces interference by decreasing the probability that a person will fixate on information that is

outdated or currently irrelevant (e.g., Hasher, Zacks, & May, 1999; Oberauer et al., 2007; Storm, 2011).

The distinction between working memory capacity and fluid intelligence is not a matter of causal flow or unique mechanisms but processing emphasis that is required by the tasks that are used to define these constructs. Tests of working memory capacity emphasize the need to retain stable access to critical information and thus highlight a person's ability to remember over the short term. Tests of fluid intelligence place a greater emphasis on cognitive flexibility. Therefore, we believe that fluid intelligence task performance is largely driven by a person's ability to break from outdated information.

Within this model, working memory capacity and fluid intelligence are correlated foremost because the tasks that measure these constructs require top-down control of both internal (e.g., mindfulness) and external (e.g., distractibility) attention in order for the test taker to stay on task. They are also correlated because maintenance and disengagement facilitate performance in both types of task. However, these constructs are also less than perfectly correlated because their respective methods of measurement place unequal emphasis on acts of maintenance and disengagement. We propose that these statements can be verified by examining correlations among individual differences in working memory capacity, fluid intelligence, and performance on fairly simple memory tasks that involve either intentional remembering or require a person to mentally break away from irrelevant information.

Maintenance as It Functions in Tests of Working Memory Capacity

Treating maintenance as the fundamental characteristic of working memory capacity is uncontroversial. Defining "maintenance" is more difficult. The most straightforward theories equate working memory capacity with individual differences in a capacity-bound storage system (Chuderski et al., 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Klingberg, 2009; Luck & Vogel, 1997), most notably the focus of attention (Cowan, 2001; Oberauer et al., 2007). From this perspective, working memory capacity is conceived of as the number of items a person can maintain in the focus of attention at any one point in time (Cowan, 2001; Cowan et al., 2005).

We do agree that developing a thorough understanding of individual differences in the size of focal attention is important to understanding complex cognition (Shipstead et al., 2012b; Shipstead, Harrison, & Engle, 2015; Shipstead et al., 2014). However, as will become clear, we treat focal attention as an outcome of effective processing, not as a precursor. Indeed, storage-centered theories of cognition have a long history of failure in accounting for phenomena such as transfer of information to long-term memory (Craik & Lockhart, 1972; Craik & Watkins, 1973; Shallice & Warrington, 1970), reading comprehension (Daneman & Carpenter, 1980; Perfetti & Lesgold, 1977), and preserved reasoning ability when short-term storage is occupied (Baddeley & Hitch, 1974; see also Crowder, 1982; Engle & Oransky, 1999; Surprenant & Neath, 2009).

Our perspective is an extension of the *executive attention account* of working memory capacity (Engle, 2002; Engle & Kane, 2004). In this account, individual differences in working memory capacity are largely explained by differences in people's ability to deploy attention in order to maintain access to information that is important, even when that information resides outside conscious awareness. A person who can consistently stabilize attentional resources on goal-relevant information will remember more items on a memory test, relative to a person with less stable attention. Individual differences in maintenance amounts can thus be seen as a byproduct of aptitude for attentive behavior and need not reflect the limits of a capacity-bound storage system (Kane, Conway, Hambrick, & Engle, 2007; Shipstead & Engle, 2013; Shipstead et al., 2015).

The chief evidence for this perspective comes from many demonstrations of a strong relation between working memory capacity and attention control (Kane, Conway, Hambrick, & Engle, 2007; Shipstead et al., 2015; Shipstead et al., 2014; Unsworth & Spillers, 2010). *Attention control* refers to the ability to engage controlled behaviors, rather than responding reflexively (e.g., antisaccade—look away from a peripheral flash). It should be noted that tests of attention control carry a low memory load and instead are oriented toward requiring participants to engage controlled processing on a consistent basis (see Kane & Engle, 2003; Roberts, Hager, & Heron, 1994). Therefore, the correlation between working memory capacity and stable attention is unlikely attributable to individual differences in fixed-capacity storage. Instead, we attribute it to the stability with which goals are maintained (see Kane & Engle, 2003).

Beyond simple laboratory tasks, individual differences in working memory capacity are apparent in many situations that have little to do with fixed information storage capacity. People with low working memory capacity experience difficulties in areas such as emotion control (Kleider, Parrott, & King, 2009; Schmeichel, Volokhov, & Demaree, 2008), susceptibility to stereotype threat (Hutchison, Smith, & Ferris, 2013), and proneness to mind wandering (Kane, Brown, et al., 2007; Mrazek et al., 2012). None of these variables involve maintaining a fixed amount of information. Instead, they speak to a person's ability to keep attention focused on relevant

information when distracting emotions, thoughts, and events are present.

A poignant example involves a recent demonstration by McVay and Kane (2012) that the long-established correlation between working memory capacity and reading comprehension (Daneman & Carpenter, 1980; Turner & Engle, 1989) is explained by attention control and mind-wandering tendencies: People with higher working memory capacity are superior readers but not because they have a larger mental workspace that allows for better integration of text. Instead, they simply are less likely to drift off mentally while reading.

The Importance of Forgetting

The flip side of selecting and stabilizing information is that, at some point, this information will become outdated. Successful disengagement from outdated information reduces interference, in and around the focus of attention. The effect is to increase the probability that relevant, instead of outdated, information will be retrieved and used in ongoing cognition.[2] In the realm of problem solving, disengagement specifically allows a person to overcome initial impressions and hypotheses that have proven to be inaccurate and therefore to avoid fixation on outdated information (e.g., Aiello, Jarosz, Cushen, & Wiley, 2012; DeCaro et al., 2015; Storm & Angello, 2010).

Our depiction of the type of thinking in which a person engages when solving complex problems draws on Smith's (2003) *paradigmatic* and *revolutionary* states of creativity. Paradigmatic thought is the initial mindset with which a person approaches a problem. Such a mindset might include a hypothesis regarding the relations among components of a problem, as well as the diagnostic methods used to test this hypothesis. These functions are readily attributed to working memory, which allows for maintenance of task-appropriate information.

During routine problem solving, paradigmatic thinking is generally useful and often leads to an appropriate solution. However, complex cognition often requires nonroutine solutions, which introduce the potential for fixation. The test taker may become stuck on inappropriate problem-solving techniques. This is akin to the perseverative tendencies shown by patients with frontal lobe damage when performing tasks that require updating of rule sets (e.g., Wisconsin card sorting; Nagahama, Okina, Suzuki, Nabatame, & Matsuda, 2005; Nelson, 1976). The ability to drop an outdated hypothesis facilitates the generation of a new one. Smith (2003) referred to this mode of reasoning as *revolutionary thought*. Our term *disengagement* refers to a similar concept. However, instead of being focused on a mode of thought, we are interested in the act of removing information from ongoing cognition so that new information can exert a greater influence.

Is working memory capacity responsible for disengagement?

A reasonable starting question is, Can working memory be the source of both maintenance and disengagement? After all, working memory capacity is strongly associated with the executive function known as *updating* (Miyake et al., 2000; Schmiedek, Hildebrandt, Lövdén, Lindenberger, & Wilhelm, 2009; Shipstead et al., submitted), which represents dynamic maintenance of information (Miyake et al., 2000). Might working memory capacity reflect a person's ability to both maintain and dump information as necessary?

Studying these types of questions can be tricky. Researchers cannot randomly assign a person's working memory capacity or fluid intelligence. Instead, they correlate individual differences in these variables to individual differences in performance of memory or attention tasks. Manipulations can then be made to the latter tasks. If the correlation with working memory capacity or fluid intelligence changes in response to these manipulations, the change is interpreted as reflecting critical aspects of individual differences in working memory capacity or fluid intelligence.

Working memory as updating. In one particularly relevant study, Wiley, Jarosz, Cushen, and Colflesh (2011) examined the correlation between working memory capacity and specific problems from Raven's Progressive Matrices (e.g., Fig. 1b). When viewed in a series, some Raven problems allow the test taker to carry over the same problem-solving strategies from one problem to the next (repeated rules). Other times, a new solution must be generated to solve the next problem (novel rules).

In their first experiment (n = 255), Wiley et al. (2011) found that performance on an operation span task (Fig. 1a) was more strongly correlated to performance on novel-rules Raven problems (r = .39) than to the repeated-rules Raven problems (r = .26). In the second study (n = 50), two difficulty-matched sets of Raven problems were created: one that included repeated rule sequences and one that required novel solutions on each problem. In this instance, the novel-rules set had a strong correlation to a composite measure of working memory capacity (operation and reading span; r = .62), while the repeated-rules set had no correlation at all (r = .02).

We attempted to replicate the second study of Wiley et al. (2011), but with a larger sample (98, rather than 50) and a within-subjects design that ensured that differences between test takers could not account for the results (Harrison, Shipstead, & Engle, 2015). However, the correlations between a working memory capacity composite score (operation span, symmetry span, and running

span) and the repeated-rules ($r = .56$) and novel-rules ($r = .58$) sets were essentially equivalent.

A shortcoming of both experiments (Harrison et al., 2015; Wiley et al., 2011) is that they are strictly correlational and thus susceptible to idiosyncrasies of certain Raven problems. Moreover, the experimenters did not have direct control of the sequence of events preceding a given Raven problem.

We therefore conducted a second experiment (Harrison, Shipstead, & Engle, 2015) in which roughly half of the test takers (total sample = 208) solved a given Raven problem as a novel rule and the others solved the same problem as a repeated rule. Five pairs of Raven problems were selected such that they involved repeated rules within the pair but novel rules between pairs. The manipulation involved the order in which items within the pairs were solved: An item could be solved first (as a novel rule) or second (as a repeated rule).

Under these controlled conditions, the correlation between working memory capacity and repeated-rules problems was now noticeably stronger ($r = .50$) than the correlation between working memory capacity and novel-rules problems ($r = .36$; difference was significant, $p = .02$). When the history of problem solving leading up to a particular problem was brought under experimental control, Harrison et al. (2015) found just the opposite of Wiley et al. (2011). Working memory capacity facilitated the solution of Raven problems by allowing test takers to represent the repeated rules across problems. That is, high working memory capacity facilitated paradigmatic, rather than revolutionary, thinking.

In the end, a relation between working memory capacity and paradigmatic thinking is in line with the general consensus of the field. As stated, in most theories working memory capacity is assumed to represent maintenance processes that allow a problem to be represented and tested (e.g., the earlier quotations). The finding of Harrison et al. (2015) simply extends this idea such that maintenance has an effect between trials.

The many sides of updating. But what of the relation between working memory capacity and the executive function known as updating? Although the correlation is strong (Schmiedek et al., 2009; Shipstead et al., 2015), it needs to be interpreted cautiously. There are many reasons why updating might be correlated to working memory capacity, and there are many things a researcher might mean when speaking of "memory updating."

To clarify this point, consider Ecker, Lewandowsky, Oberauer, and Chee (2010) who hypothesized that updating (e.g., Miyake et al., 2000) can be decomposed into three functions: retrieval, transformation, and substitution. *Retrieval* refers to the ability to accurately recall information for updating; *transformation* refers to

processes that allow the retrieved component to be changed.

These aspects of updating are apparent in a complex span task (Fig. 1a). Each time the processing task is performed, the to-be-remembered list must be retrieved and attended (recall) so that a new item can be appended to the maintained list (transformation).

Using a task that required continuous updating of three representations, Ecker et al. (2010; $n = 97$) found that the accuracy with which retrieval and transformation are carried out correlates to working memory capacity (as measured by complex span), above and beyond a general memory updating ability. Retrieval and transformation are apparent in the performance of the complex span.

Substitution is closer to our concept of disengagement. It refers to the act of replacing the contents of memory with new information. Ecker et al. (2010) found no special relation between working memory capacity and accuracy with which substitution is carried out. A follow-up study ($n = 167$), which was specifically focused on the speed with which substitution occurs, also did not produce a relation to working memory capacity (Ecker, Lewandowsky, & Oberauer, 2014). It should be noted that both studies by Ecker et al. successfully produced reliable individual differences in the speed and accuracy with which memory updating occurs. Yet substitution had no special relation to working memory capacity.

To be clear, we do not present this as evidence that working memory capacity is unrelated to disengagement. This claim can only become apparent among many contexts, and the studies of Ecker and colleagues (Ecker et al., 2014; Ecker et al., 2010) only provide one such context. What these studies do indicate is that the process of updating is multifaceted, and the strongest relations that working memory capacity had to this particular updating task were actions that involved maintaining access to memory of the most current information.

The idea that individual differences in working memory capacity do not account for disengagement echoes recent sentiment in the problem-solving literature. While stable maintenance is important for representing problem, it can also prevent insight if a person is overly focused on initial problem-solving attempts (Aiello et al., 2012; DeCaro & Beilock, 2010). In several studies, high working memory capacity has been implicated specifically as the source of fixation that prevents problem restructuring (DeCaro, Van Stockum, & Wieth, 2015) and the discovery of more efficient problem-solving methods (Beilock & DeCaro, 2007). In some cases, these issues can be alleviated through mild alcohol intoxication, which reduces executive function (Jarosz, Colflesh, & Wiley, 2012).

We do agree with the basic premise of Wiley et al. (2011) that disengagement is an important component of

complex cognition. However, our most recent findings indicate that disengagement is more strongly reflected by individual differences in fluid intelligence.

Disengagement from proactive interference: A function of fluid intelligence?

A direct line between problem solving and disengagement comes from a creativity study by Storm and Angello (2010; see also Storm, 2011). They argued that creative insight is facilitated by the ability to suppress inappropriate solutions.[3]

To test this idea, Storm and Angello (2010) gave test takers (*n* = 72) a series of Remote Associates Test problems in which three words are presented, and the test taker must generate a word that combines them (e.g., "manners," "tennis," and "round" are related by the word "table"). The challenge of this task lies in the fact that the target word is not the primary associate of any of the others. Essentially, Remote Associates problems can lead to fixation on first impressions.

Storm and Angello (2010) found that the likelihood of a test taker overcoming fixation on Remote Associates problems was predicted by performance on a retrieval-induced forgetting task (i.e., forget unpracticed information after practicing other information; see Anderson, Bjork, & Bjork, 1994). By the account of Storm and Angello, people whose memory is aided by the ability to forget (in this case, suppress) unused information can use this mechanism to move on readily from outdated impressions. Thus they are well equipped to solve Remote Associates problems.

More direct to the present subject, Colom et al. (2008; Experiment 3) reported that controlling variance that is associated with short-term and working memory capacity does not eliminate the correlation between memory updating and general intelligence (*n* = 289). It should be noted that in this study general intelligence was primarily defined through fluid intelligence. Memory updating and reasoning ability share components that are not explained by maintenance-related variables.

Our own indication that we can extend this line of thinking to individual differences in fluid intelligence came from a series of studies by Shipstead and Engle (2013) using the visual arrays task (Fig. 3). In this task, a pattern of items (typically between four and eight) is briefly displayed on a monitor (target; Fig. 3). Next, the screen goes blank for a few seconds (retention interval; Fig. 3). Finally, a probe pattern is presented that is either the same as the initial display or has one item changed (probe; Fig. 3). The test taker makes a same/different judgment. Visual arrays task performance has been overwhelmingly interpreted as reflecting the storage capacity of working memory (Awh, Barton, & Vogel, 2007; Chuderski et al., 2012; Cowan et al., 2005; Fukuda,
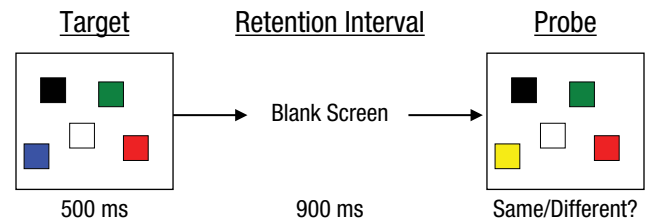
Fig. 3. Sequence of events in a typical visual arrays task. First, a target array is briefly displayed. Second, a blank screen is shown. Third, a probe display is shown and the test taker decides whether it matches the target display.

Vogel, Mayr, & Awh, 2010; Luck & Vogel, 1997; McNab & Klingberg, 2008; Rouder, Morey, Morey, & Cowan, 2011; Saults & Cowan, 2007).
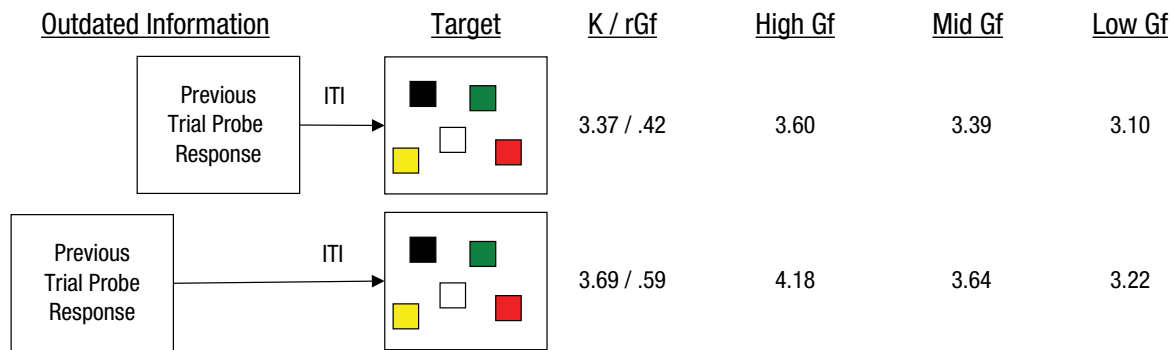
The point of Shipstead and Engle's (2013; see also Souza & Oberauer, 2015) study was to show that performance on visual arrays is not attributable to a storage system but instead reflects active processing (e.g., attention control and retrieval). They illustrated this point via manipulations of temporal discriminability.

Temporal discriminability can be understood by looking at the left hand side of Figure 4, which displays different delays between the end of one trial and the beginning of the next. Relatively long delays between two trials reduce memory interference by isolating the most recent trial in time, reflected in increased estimates of storage capacity—the number of items in the display to which a test taker can accurately respond. Conversely, relatively short delays create a situation in which the current trial and the previous trial are compressed in time. The effect is increased interference and, as a result, decreased estimates of storage capacity.

Shipstead and Engle (2013; Experiment 4; *n* = 53) included participants who had been prescreened on several measures of working memory capacity and fluid intelligence. If working memory capacity is related to disengagement (e.g., as was argued by Wiley et al., 2011), then one would expect longer delays between trials to affect the correlation between visual arrays performance and working memory capacity because the manipulation affects the amount of time that people have to disengage from outdated information.

If working memory capacity is related to disengagement, one of two results should obtain. On one hand, low disengagers might improve their performance with the extra time between trials, making the scores of high and low working memory capacity individuals more similar. On the other hand, high disengagers might be at even more of an advantage, since they are specifically equipped to break from outdated information, which would lead to an even greater difference between the scores of high and low working memory capacity

Outdated Information		Target	K / rGf	High Gf	Mid Gf	Low Gf
Previous Trial Probe Response	ITI →	[array]	3.37 / .42	3.60	3.39	3.10
Previous Trial Probe Response	ITI →	[array]	3.69 / .59	4.18	3.64	3.22

Fig. 4. The relationship of long and short intertrial intervals to individual differences in fluid intelligence. Adapted from "Interference Within the Focus of Attention: Working Memory Tasks Reflect More Than Temporary Maintenance," by Z. Shipstead & R. W. Engle, 2013, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*, p. 285. Copyright 2013 by the American Psychological Association. Reprinted with permission. ITI = inter-trial interval; Gf = fluid intelligence; K/rGF = correlation between estimated storage capacity and fluid intelligence.

individuals. However, in terms of working memory capacity, neither effect was found.[4]

In contrast, the correlation between visual arrays performance and fluid intelligence did change as a product of the length of time between trials (Shipstead & Engle, 2013). The overall data revealed that estimated storage capacity increased in response to a longer between-trial delay (from 3.37 items to 3.69 items; Fig. 4). Unlike the correlation to working memory capacity, the correlation to fluid intelligence changed along with this increased performance. Following a short intertrial interval, the correlation between visual arrays performance and fluid intelligence was .42 (see Fig. 4). Following a long intertrial interval, the correlation increased to .59. This trend is consistent with the hypothesis that longer intervals increase the advantage of high disengagers.

The result of a post hoc examination of the data was consistent with this interpretation. Only people with high fluid intelligence were able to take advantage of the extra time. They showed a significant increase in their accuracy after a long intertrial interval (from 3.60 items to 4.18 items; Fig. 4). People with moderate fluid intelligence only showed nonsignificant increases (from 3.39 items to 3.64 items). People with low fluid intelligence showed no signs of increased attentional capacity following a long delay (from 3.10 items to 3.22 items). Shipstead and Engle (2013) thus surmised that higher fluid intelligence is indicative of self-initiated disengagement: Only people with above-average fluid intelligence were capable of using the longer interval to reduce memory interference.

n-*Back: Working memory capacity, fluid intelligence, and lure items.* Shipstead and Engle (2013) argued that individual differences in working memory capacity and fluid intelligence make unique predictions about performance on memory tests. While high working

memory capacity is important for making discriminations when memory interference is high (see Footnote 6), high fluid intelligence seems to facilitate such discriminations by ridding focal attention of inappropriate information (actively reducing interference). However, the analysis by Shipstead and Engle was, admittedly, post hoc, and a conceptual replication was required.

We tested this hypothesis using *n*-back tasks in which the position of lure items was manipulated.[5] In these tasks, the test taker was presented with a series of images for 2 s each and was required to make a simple judgment: Did the currently presented item match the item that was presented three items back (i.e., target)?

A critical component of *n*-back tasks is the presence of lures (Burgess, Gray, Conway, & Braver, 2011; Gray, Chabris, & Braver, 2003; Kane, Conway, Miura, & Colflesh, 2007). We define lures as items that repeat in positions other than 3-back. These items add challenge to the task by preventing test takers from answering solely on the basis of familiarity.
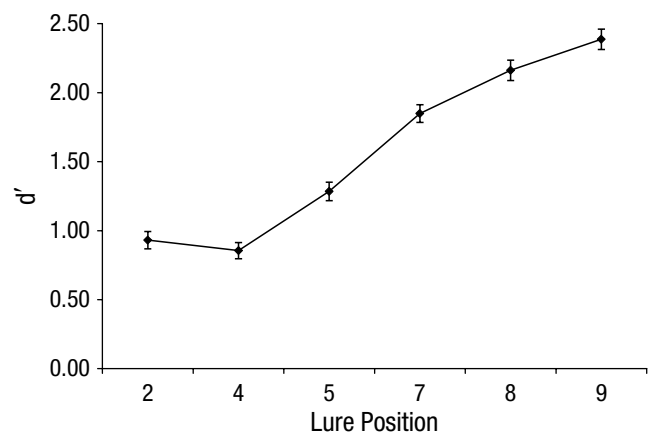
Fig. 5. Graph of d′ by lure position. Error bars represent ±1 standard error of the mean.

One would expect the *n*-back task to be easy when lures are distant (7-, 8-, or 9-back), relative to when they are near (2-, 4-, or 5-back) because the near lures are either actively maintained (2-back) or recently outdated (4-back). The distant items have been outdated for some time and thus are likely forgotten, due to mechanisms such as activation decay (e.g., Cowan, 1988, 1999) or poor temporal discriminability (e.g., Baddeley, 1976; Crowder, 1976).

We tested people (*n* = 534) using six different *n*-backs. Half of the tasks had lures in the near positions (2-, 4-, and 5-back), and half had lures in the distant positions (7-, 8-, and 9-back). For each of these tasks, we constructed three versions using different types of stimuli (words, faces, and wingdings). Composite scores are reported.

Figure 5 reveals that our expectation regarding lure-related difficulty obtained. Each point represents d′ calculated with hit rate at 3-back and false alarms at each lure position. As lures became more distant, d′ increased—a sign that the task became easier to perform.

Given this trend, the intuitive expectation is that the correlation between *n*-back performance and both fluid intelligence and working memory capacity is strongest with the near-lures. Cognitive abilities such as fluid intelligence and working memory capacity, which manage interference, should be most critical when high interference makes a task difficult.

Yet, the previous finding by Shipstead and Engle (2013) gave us our first reason to be skeptical of this assumption. When visual arrays got easier (as reflected in higher estimated storage capacity), it provided a better reflection of fluid intelligence. This specifically occurred because only people with high fluid intelligence were able to take advantage of the longer between-trial delay.

A second reason for skepticism comes from a study by J. McCabe and Hartman (2008; see Experiment 1, 3-back condition), which served as inspiration for this experiment. They examined *n*-back performance for young (18–30 years; *n* = 36) and older (60+ years; *n* = 36) adults. Overall, older participants had more difficulty with lures than did young participants. Young participants reached asymptotic release from the effects of lures at 5-back, while older adults still were showing release effects at 6-back (the longest distance in this study). As the task got easier, the mean performance improvements were mainly attributable to young participants. Older participants continued to make inappropriate responses to lures, even as these lures became quite removed from the 3-back position.

If we treat advanced age as a stand-in for lower cognitive abilities (Ackerman, 2000; D. P. McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Park et al., 1996; Salthouse & Babcock, 1991), one might expect a similar
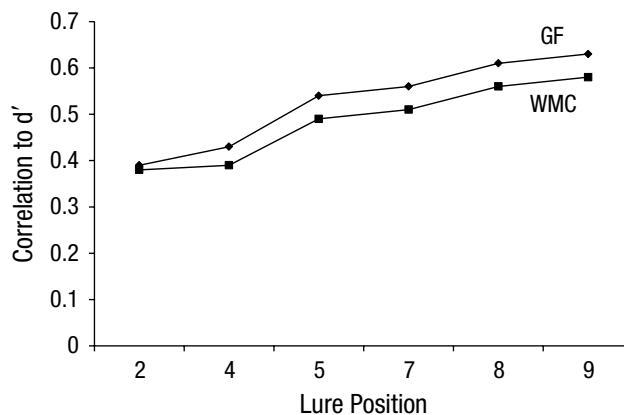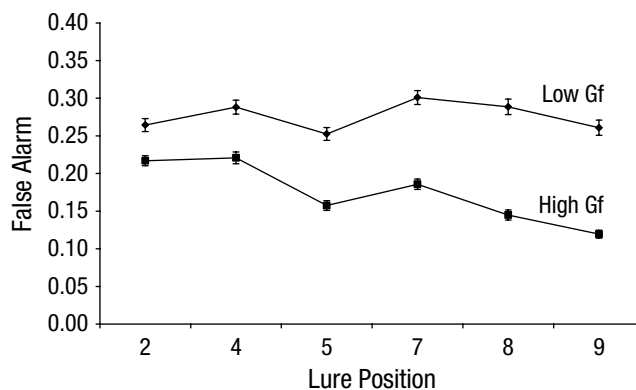

Fig. 6. Correlation of fluid intelligence (Gf) and working memory capacity (WMC) to d′.

effect in our data. That is, the increased d′ with lure position would be attributable to higher fluid intelligence individuals disengaging from no-longer-relevant material, while lower fluid intelligence individuals continue to produce false alarms in response to outdated information.

Figure 6, which presents the correlations between d′ and both fluid intelligence and working memory capacity, is consistent with this counterintuitive hypothesis. As lures became more distant, *n*-back performance became more strongly predictive both of fluid intelligence and of working memory capacity.

This otherwise surprising relation is clarified in Figure 7, which presents tendency toward false alarms for people with high and low fluid intelligence (median split). Across all positions, people with higher fluid intelligence are less prone to false alarms than are people with lower fluid intelligence.[6] This difference is smallest for the near-lure positions and steadily increases as lures become more distant (linear interaction of Lure Distance × Fluid

Fig. 7. False alarms by lure positions for individuals with high and low fluid intelligence (Gf; median split). Error bars represent ± 1 standard error of the mean.

Intelligence interaction, $p < .001$, $\eta^2_p = .01$). The reason that the correlation between d′ and fluid intelligence increases as lures become more distant is that people with lower fluid intelligence do not benefit as much from lures being distant as do people with higher fluid intelligence. These groups differ in their ability to disengage from outdated information.[7]

It is critical in these interpretations that we should be able to attribute this trend to fluid intelligence, rather than to working memory capacity. The top line in Figure 8 displays the correlation of fluid intelligence to false alarms across different lure positions (negative correlation is reversed for ease of viewing). This follows the same trend as d′ did in Figure 5.

The bottom line in Figure 8 displays the partial correlation between fluid intelligence and false alarms across lure positions with working memory capacity statistically controlled. Although the correlation is reduced, it remains strong in the distant positions. It is important to note that the steady increase across lure positions remains and thus cannot be attributed to working memory capacity.

The top line of Figure 9 displays the correlation between working memory capacity and false alarms at different lure positions. As with fluid intelligence, there is a steady increase across positions. However, the bottom line shows the correlation between working memory capacity and false alarms once fluid intelligence is controlled; the correlation is all but erased. The only two data points in which false alarms are statistically related to working memory capacity are lure potions 8 and 9. Due to the slightness of these relations as well as the large sample size ($n = 534$), one might question the meaningfulness of these data points. At any rate, it is clear that these data are strongly consistent with the position that fluid intelligence is largely responsible for disengagement from outdated information. The relation between working memory capacity and false alarms across lure positions is essentially eliminated when it is assumed that everybody has the same fluid intelligence.

Finally, we examined hit rate, or accuracy of recognizing an item in the 3-back position. Figure 10 presents the data as a median split of high and low fluid intelligence. Overall, people do produce higher hit rates when lures are distant. However, this effect is not explained by fluid intelligence, as both high and low fluid intelligence individuals experienced equivalent improvements (Lure Distance × Fluid Intelligence interaction, $p = .99$, $\eta^2_p < .001$). The results were basically identical for working memory capacity ($p = .45$, $p < .001$).

Table 1 displays the correlations of fluid intelligence and working memory capacity to hits for near and for distant lures. Although hit rate was unimportant to the original trend from Figure 5, the partial correlations are nonetheless telling. Focusing on near lures, we found
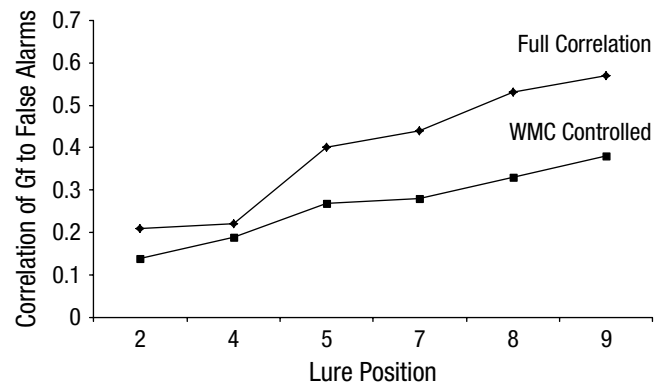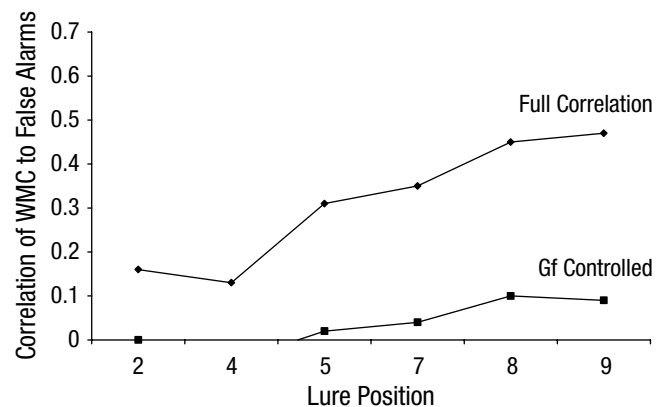

Fig. 8. Correlation of fluid intelligence (Gf) to false alarms. Note that the direction of the correlations has been reversed for ease of viewing. WMC = working memory capacity.

that when working memory capacity was controlled, the otherwise strong correlation between fluid intelligence and hits dropped to a nonsignificant .08 ($p = .06$).[8] Conversely, the correlation of working memory capacity to hits remained relatively strong when fluid intelligence was controlled. This returns us to the first of our main themes: Working memory capacity primarily reflects the ability to retain access to relevant information when interference is high (see Shipstead & Engle, 2013; Unsworth & Engle, 2007a, 2007b).

Relating Working Memory Capacity to Fluid Intelligence

Respectively treating maintenance and disengagement as the defining attributes of individual differences in working memory capacity and fluid intelligence creates an easily understood distinction between these constructs but does not make their relation explicit. Although we

Fig. 9. Correlation of working memory capacity (WMC) to false alarms. Note that the direction of the correlations has been reversed for ease of viewing. Gf = fluid intelligence.
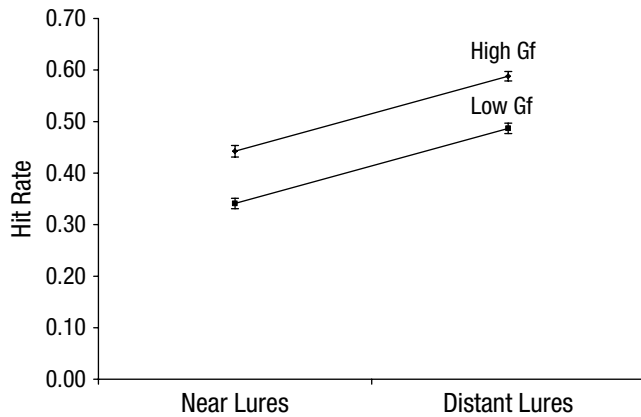
Fig. 10. Hit rate for high and low fluid intelligence (Gf; median split) individuals when lure positions are 2, 4, and 5 (near) or 7, 8, and 9 (distant). Error bars represent ± 1 standard error of the mean.

attribute this correlation largely to top-down organization provided by executive attention (e.g., Level 1 of Fig. 2), it is also instructive to think about the relation in terms of complex task performance (Level 3). At this point, discussion of storage capacity becomes germane.

Focal attention: Clarifying Level 2 from Figure 2

Although we explicitly avoided treating storage capacity as a causal mechanism, this does not mean that we dismiss the concept altogether. After all, it is perfectly reasonable to argue that working memory capacity tasks provide an estimate of the amount of useful information that a person can retain in and around the focus of attention (at least for practical purposes). However, instead of treating this as a mechanism of working memory capacity or a cause of fluid intelligence, we view estimates of storage-capacity (e.g., visual arrays scores; Fig. 4) as being the result of a balance between maintenance and disengagement processes.

This idea can be represented using the concentric model of working memory capacity (Fig. 11) by Oberauer

Table 1. Correlations Between *n*-Back Hits and Both Fluid Intelligence and Working Memory Capacity

Lure Distance	Hits	
	Near Lures	Distant Lures
Correlation to Gf	.33*	.40*
Controlling for WMC	.08†	.16*
Correlation to WMC	.38*	.40*
Controlling for Gf	.21*	.17*

Note: Gf = general fluid intelligence; WMC = working memory capacity.
*p < .05. †p < .10

and colleagues (Oberauer, 2002; Oberauer et al., 2007). This perspective shares a great deal of conceptual overlap with Cowan's (1988, 1999, 2001) focal-attention-based model of working memory capacity, but it differs in the mechanisms of maintenance. Cowan's (1988, 1999, 2001) model depicts individual differences in working memory capacity as individual differences in the number of items a person can simultaneously maintain in the focus of attention. Most people can store between three and five items in focal attention. Greater maintenance capacity means more information is protected from proactive interference.

Oberauer's (Oberauer, 2002; Oberauer et al., 2007) alternate perspective of focal attention maps well onto our present ideas. The concentric model of working memory is displayed in Figure 11. Black dots represent currently active chunks of long-term storage. Unlike Cowan in the multichunk model, Oberauer assumes that the focus of attention operates on only one chunk at a time (see also McElree, 2001; Shipstead & Engle, 2013; Verhaeghean & Basak, 2005). This is represented by the inner circle in Figure 11. The three-through-five-item capacity limitation (e.g., Cowan, 2001) does not represent a fixed-capacity storage system but instead is reached by the creation of temporary associations (bindings) between the focus of attention and chunks of active memory. This is referred to as the *region of direct access* and is represented by the outer circle. This component is a flexible portion of memory in which temporary bindings can be created between otherwise unassociated chunks of long-term memory, thus allowing for novel combinations to be created.

The critical distinction between Cowan's (1988) focus of attention and Oberauer's (2002) region of direct access is interference. While Cowan proposed that the focus of attention is free of interference and is limited by absolute storage capacity, Oberauer envisioned the region of direct access as being subject to interference such as item similarity (overwriting) and competition for representation (cross-talk).

Relevant to our perspective, old bindings that have not been properly erased are another factor that limits the region of direct access (Oberauer, 2001). Outdated but active bindings lead to a buildup of interference, in which old information makes the retrieval of relevant information more difficult (e.g., Wickens, Born, & Allen, 1963).

A memory test might reveal that a person can remember three items accurately. From Cowan's perspective, this revelation would mean that focal attention was storing those items and protecting them from proactive interference. Oberauer's model introduces the possibility that a person could be maintaining many more than three items but be able to recall only about three due to cognitive noise generated by unnecessary maintenance. This
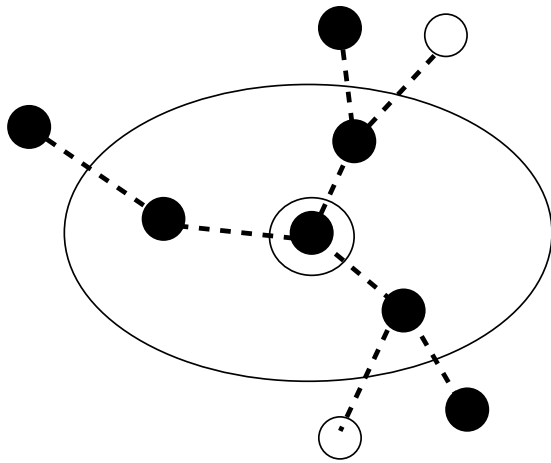
Fig. 11. Oberauer's (2002) concentric model of working memory. Dots represent information chunks. Black dots are currently active. The outer circle represents the region of direct access in which chunks can be associated in novel patterns. The inner-circle is a one-item focus of attention. Adapted from "Access to Information in Working Memory: Exploring the Focus of Attention," by K. Oberauer, 2002, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, p. 50. Copyright 2002 by the American Psychological Association. Reprinted with permission.

position also is evident in Level 2 of our model from Figure 2. Maintaining relevant information and disengaging from irrelevant information are both seen as critical components of effective cognition and critical determinants of the effective size of focal attention.

Defining capacity. Oberauer's (Oberauer, 2002; Oberauer et al., 2007) perspective bridges the gap between our capacity-as-aptitude-for-maintenance perspective and the capacity-as-size-of-maintenance perspective taken by other researchers (e.g., Chuderski et al., 2012; Cowan, 2001). Assume, for a moment, that there is no limit on the number of bindings that may be created (or size of storage buffer). While this arrangement might seem advantageous, it is not. There will be a tipping point: If everything is stored in temporary memory, then effectively nothing stored in temporary memory (see Hamilton & Martin [2007] for a relevant case study).

As more information is maintained, interference increases within temporary memory—and with it the probability of attending to irrelevant information.[9] Proper coordination of maintenance and disengagement balances the benefit of maintenance against the detriment of too much maintenance. The effect is a phenomenon that many psychologists interpret to be a "limited" or "fixed" capacity storage system.

Divergence from Oberauer's model. Our chief similarity to Oberauer's (2002; Oberauer et al., 2007) model is that we treat individual differences in working memory

capacity as individual differences in the binding process. In terms of problem solving, working memory specifically represents the creation and stabilization of representations in which hypotheses might be tested (paradigmatic thought; Smith, 2003). Our chief divergence is that we treat the unbinding process as the hallmark of fluid intelligence. That is, fluid intelligence foremost reflects a person's ability to intentionally unbind an untenable or no longer useful association, thus facilitating problem solving (e.g., revolutionary thought; Smith, 2003).

The distinction between task and ability

The strong correlation between working memory capacity and fluid intelligence need not be seen as points in a sequence (i.e., working memory maintains information, and this facilitates reasoning processes). Instead, the correlation arises from the reciprocal roles that the underlying abilities play in creating and managing a mental context in which information can be represented and potential solutions evaluated.

To clarify this concept, consider how these processes might function when one is performing various tasks. In a working memory capacity task, maintenance is at a premium, but forgetting is at least a secondary influence. Remembering information from the most recent trial is facilitated by reducing proactive interference from previous trials (Kane & Engle, 2000; Kincaid & Wickens, 1970; Wickens et al., 1963; Wixted & Rohrer, 1994). This point is represented in Figure 12.

In the complex span task, the most salient obstacle to accurate task performance is an interpolated processing task, which displaces to-be-remembered information from focal attention. Within the context of this type of task, maintenance is at a premium. However, this does not mean that disengagement is irrelevant. Proactive interference (lingering bindings) from previous trials provides a second source of forgetting (Unsworth & Engle, 2007a). Between-trial disengagement reduces the need to discriminate between currently relevant and outdated memories.

The relation of these processes to completing a fluid intelligence task is made clear in Figure 13. When one is involved in solving a problem in a fluid intelligence task, maintenance allows a person to form a stable representation of the problem in which testing of hypotheses can be carried out. In particular, stabilized attention helps that person to avoid being drawn into salient distraction, such as lure responses that give rise to the false impression of a correct solution (Jarosz & Wiley, 2012). In addition, previous learning is important to organizing this initial representation (e.g., recent trials [Wiley et al., 2011], experience with similar tests).
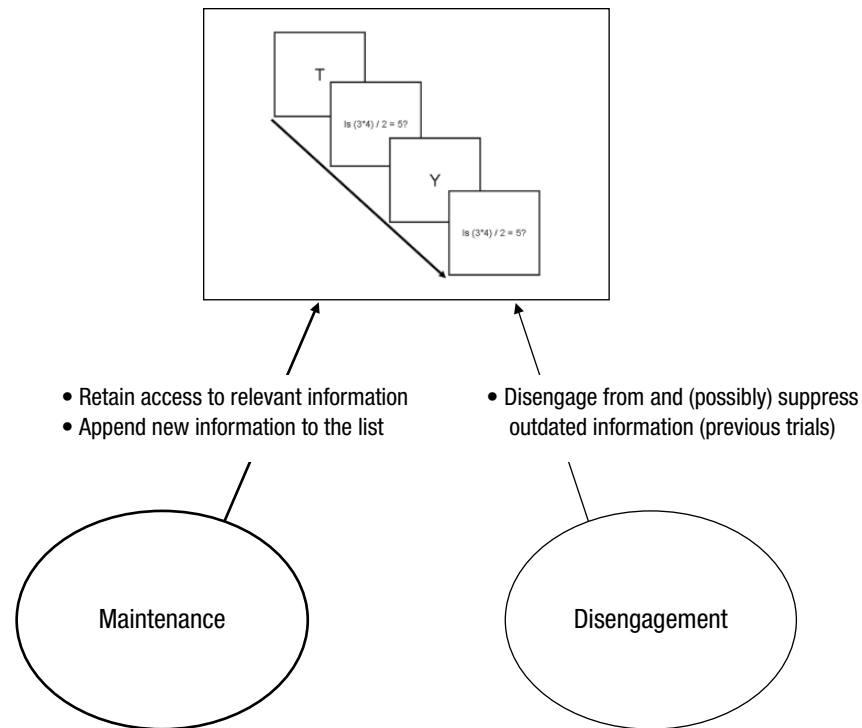
Fig. 12. The proposed roles of maintenance and disengagement in performance of a working memory capacity task. Bolded circle indicates process of primary relevance.

However, reasoning is not static. At some point, a criterion will be reached at which the hypothesis is deemed correct or incorrect. If correct, a response will be given. If incorrect, the hypothesis must be forgotten so that a new one may be formed and tested. This action is the chief determinant of the ability commonly referred to as fluid intelligence. Fluid intelligence represents the transformation of an initial impression into a new interpretation. More directly, fluid intelligence is the process of learning that certain information does not belong within a given mental context.

Recently, Chuderski (2013; but see Colom et al., 2015) found that working memory capacity and fluid intelligence are nearly isomorphic when fluid intelligence tasks are conducted under speeded conditions (~10–20 min) but only moderately related under more standard timing (~45–60 min). Chuderski argued that time pressure allows for a lower degree of abstract relational learning to occur. The present perspective may shed further light on this finding. Time pressure may place a premium on simply being able to represent problems so that they may be tested, thus increasing reliance on maintenance. With lower pressure to solve problems quickly, test takers can place more emphasis on testing several different hypotheses, thus increasing the importance of disengagement and allowing a differentiation of fluid intelligence from working memory.

Integration With the Concept of Intelligence

We foremost view the present work as a theory of how executive attention functions within the context of working memory and fluid intelligence tasks. Human intelligence is much broader concept than we discuss here (Nisbett, 2009), encompassing concepts such as emotional intelligence (Mayer, Salovey, & Caruso, 2008) and self-discipline (Duckworth & Seligman, 2005), among others. Nonetheless, our discussion is couched within the context of novel problem solving, and it is therefore important that we fit it within the broader intelligence literature.

Carroll's (1993) three stratum model of cognitive abilities provides a starting point for such discussion. This theory conceives of cognitive abilities as arising at three levels of generality. The highest stratum is general ability (g), which we conceive of as similar to executive attention. From the present perspective, the ability to organize attentional resources around goal-relevant tasks accounts for positive manifold (Spearman, 1904)—the tendency of desirable cognitive traits to be positively correlated with one another.

The lowest stratum of Carroll's (1993) theory is composed of numerous narrow abilities, each of which is highly specialized. From our perspective, narrow abilities
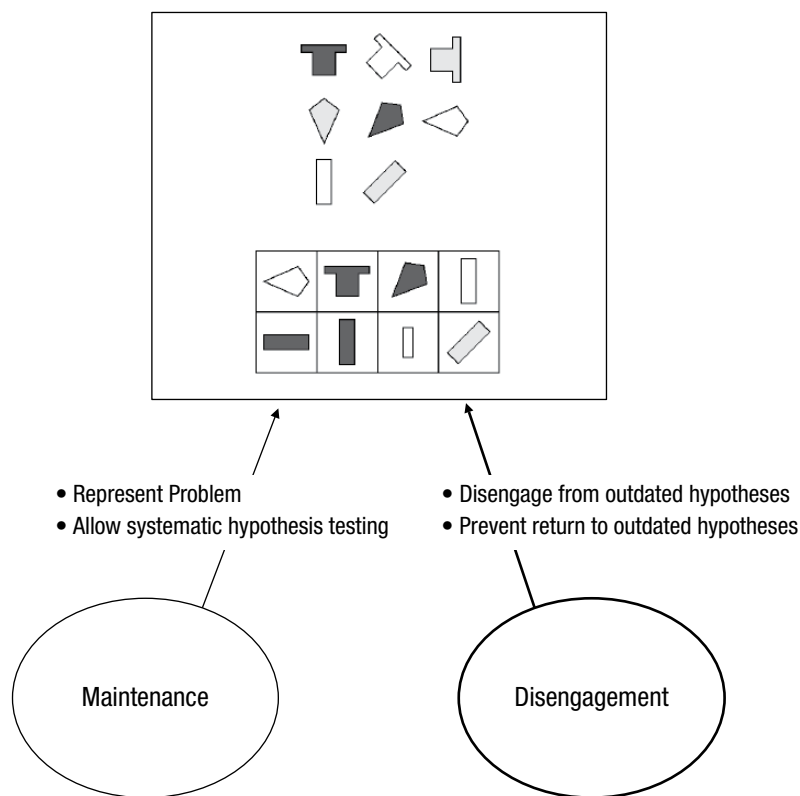
Fig. 13. Proposed roles of maintenance and disengagement in performance of a fluid intelligence task. Bolded circle indicates process of primary relevance.

are the mechanisms that allow for maintenance and disengagement. These might include binding, storage, sustained attention, suppression, inhibition, episodic tagging, and other components that allow attention to be stabilized and destabilized in a controlled manner.

Our model (Fig. 2) excluded the middle stratum, which includes numerous broad abilities such as fluid intelligence (referred to as Gf), crystalized intelligence (referred to as Gc), and general memory and learning (referred to as Gy). In Carroll's (1993) model, narrow abilities are conceived of as being reliant on the broad abilities.[10] Our view is less unidirectional. Broad abilities arise as the product of top-down executive attention combining with the narrow abilities that are required to perform a specific task. Executive attention is the common factor among broad abilities, while distinctions arise from the degree to which narrow abilities are called upon by particular psychological tests (e.g., Fig. 12 and Fig. 13). In this view, broad abilities are not fixed resources but arise due to demands that are specific to a variety of tasks.

Fluid and crystalized intelligence

Among the most common ways that varieties of intelligence are distinguished is along the dimensions of fluid and crystalized intelligence (Carroll, 1993; Horn, 1968; Horn & Cattell, 1966). Whereas fluid intelligence is seen as the ability to reason with novel information, crystalized intelligence is seen as the ability to put previously learned information to use.

Although crystalized intelligence seems to provide a strong conceptual contrast against fluid intelligence, the distinction is not that straightforward. As argued by Cronbach (1990), fluid and crystalized intelligence likely exist along a spectrum. At the extreme-fluid-intelligence end would be matrix-reasoning tasks, such as shown in Figure 1b. At the extreme-crystalized-intelligence end would be factual knowledge.

Most tasks, however, are not at the extremes and actually blend components of fluid and crystalized intelligence. As examples, Cronbach (1990) offered activities such as interpreting tables and diagrams or performing an analogy task. This view fits well within our perspective in which broad abilities are largely discriminated by task-specific demands. Given our previous arguments, it seems reasonable to assume that working memory capacity is also an important part of the equation. Indeed, working memory capacity is not only separable from fluid intelligence but from crystalized intelligence as well.

For instance, Meinz and Hambrick (2012) demonstrated that Texas Hold'Em poker skills are predicted by both working memory capacity and poker knowledge. It is important to note that dedicated practice does not eliminate working memory capacity as a predictor of performance (Hambrick & Meinz, 2011). In another study, Meinz and Hambrick (2010) found that although deliberate practice was the best predictor of the ability to sight-read piano music, a consistent effect of working memory capacity remained from early learners to experts.

In terms of the actual acquisition of knowledge, the historic perspective has been to treat fluid intelligence as the mechanism of attainment (Horn & Cattell, 1966). For instance, Carroll (1993) pointed out that numerous studies have shown fluid intelligence to be important for acquiring knowledge in schools. Yet evidence suggests working memory capacity is also a critical factor. For instance, Shute (1991) found that working memory capacity was the best predictor of the rate at which people acquired computer programming knowledge, above and beyond traditional predictors of intelligence. Other studies have shown that working memory capacity predicts the rate at which children acquire the syntax of their native language (Engel de Abreu, Gathercole, & Martin, 2011).

However, in terms of working memory capacity and knowledge acquisition, the rich do not always get richer. Although Hambrick and Meinz (2011) provided a number of examples in which the effect of working memory capacity remained important across different levels of learning, the converse of this observation is that people with higher working memory capacity do not always excel at learning, relative to people with lower working memory capacity. At present, the safe statement is that working memory, fluid intelligence, and crystalized intelligence are all important to performing a wide array of tasks. Their presence or absence (and their effects on one another over time) is likely determined by the nature of the task that is being performed.

Abilities as process

As stated, we view broad abilities (e.g., working memory capacity, fluid intelligence, and crystalized intelligence) as the result of active processing between executive attention and specialized mechanisms (e.g., maintenance and disengagement). Therefore, our ideas fit better within process-oriented views of human abilities than within structure-oriented psychometric theories (see, Sternberg, 1985b). Sternberg's (1984, 1985a, 2005) triarchic theory of successful intelligence provides a model of real-world function in which our ideas can be expanded.

The triarchic theory includes three major divisions. The first is the internal mechanisms of intelligent functioning, subdivided into metacomponents, performance components, and knowledge components (Sternberg, 2005). This aspect of the theory has the most obvious relation to our own ideas, as they were laid out in Figure 2.

The concept of metacomponents maps well onto our idea of executive attention. *Metacomponents* refers to executive processes that carry out functions such as recognizing a problem, selecting a strategy, monitoring the problem-solving attempt, and evaluating outcomes.

Performance components carry out the instructions of metacomponents. Mapping this idea to our theory, when a problem-solving attempt is judged to be inadequate by higher-order executive processes, disengagement mechanisms will be called upon to refresh focal attention. The success of this action affects further strategy selection and problem monitoring at the executive level.

Finally, knowledge acquisition components are the processes that allow for acquisition of new information, particularly information that guides metacomponents and performance components. Sternberg (2005) highlighted three: selective encoding, selective combination, and selective comparison. These functions seem to fit well within traditional ideas of working memory capacity—in particular, the ideas that attention control keeps people focused on relevant information (Engle, 2002; McVay & Kane, 2012) or that working memory allows a work space in which representations can be constructed and compared (Oberauer et al., 2007).

From our perspective, one might think of abilities such as working memory capacity as knowledge acquisition components. Similar to our discussion of Carroll's (1993) broad abilities, this would place knowledge acquisition components in a more abstract position. That is, they are the result of the quality of interaction between metacomponents and performance components.

The second aspect of the triarchic theory deals with the question of *when* these mechanisms lead to what can be called *intelligent behavior*. For instance, different components may be differently important to intelligent behavior at different levels of experience. Of particular interest, Sternberg (2005) noted that tasks that test a person's ability to deal with novelty tend to have the strongest relationship to general intelligence (Snow & Lohman, 1984). From our view, the essence of dealing with novelty is an ability to disengage from outdated information and ideas (see also Smith, 2003; Storm & Angello, 2010).

Finally, triarchic theory emphasizes that intelligence occurs, not simply in the head, but in the external world as well. Sternberg (1984, 1985b, 2005) emphasized adaptation to, shaping of, and selection of an environment. These topics are a bit beyond the boundaries of the present theory; however, they do provide a point at which we can reemphasize our focus on the environment in determining mental abilities (e.g., Level 3 of Fig. 2; Figs. 12

and 13). Human abilities are not simply fixed processes or resource pools in the head but a dynamic interaction of such mechanisms with the environment. The distinction between working memory capacity and fluid intelligence does not begin with fixed abilities but arises due to demands that are made by the environment (e.g., tests of working memory capacity or fluid intelligence).

Integration With Concepts on Memory and Cognition

Intentionality of disengagement

One concern that we must reconcile is the contrast of our findings against a study by Bunting (2006). He demonstrated that the correlation between operation span and Raven (Fig. 1) performance was strongest after a buildup of proactive interference (similar memory items in complex span) and weakest after a release (change in memory items in complex span). This finding seems to contradict our position that people with low fluid intelligence have difficulty disengaging from outdated information: The correlation should have been strongest after a release from proactive interference.

We have several reasons for favoring our data (Shipstead & Engle, 2013 and the *n*-back study). These include the use of a broader sample of participants (community and college) and the use of multiple measures of fluid intelligence. It should further be noted that, contrary to the results of Bunting (2006), both Foster et al. (2015) and Salthouse and Pink (2008) found that the correlation between fluid intelligence and trial-by-trial performance on a working memory capacity task does not increase as proactive interference builds.

The critical distinction between our and Bunting's (2006) studies may be the method of release from proactive interference. Bunting induced a release from proactive interference by changing the nature of to-be-remembered stimuli, while our studies (Shipstead & Engle, 2013; present *n*-back) were subtler (delay between trials) or required active monitoring on the part of the test takers (keeping track of relevant information in the face of intervening items). In Bunting's case, giving people a fresh memory cue may have led to an exogenously driven release from proactive interference. In our data, we suspect that disengagement was endogenously driven.

In other words, the difference between studies may be the locus of release. In a study like the one by Shipstead and Engle (2013) in which a time-based release from proactive interference was used, the ability to break from outdated information is largely driven by a person's ability to constrain cognition to relevant time periods. That is to say, it is self-directed (see Unsworth & Engle, 2007a).

Bunting (2006) induced a release from proactive interference by changing the type of information a person was required to remember (digits or words). This release provides the test taker with a fresh memory cue with which only recent information has been associated (see M. J. Watkins, 1979; Watkins & Watkins, 1975). That is to say, the release is driven by a change to external context.

The inconsistency between the present data (visual arrays; *n*-back) and Bunting (2006) requires direct examination, but the idea that intentionality is a critical component of disengagement (as it is measured by fluid intelligence tasks) suggests other possibilities that need to be explored. For instance, Anderson (2005) reviewed the literature on tasks that are used to measure inhibition and came to a conclusion similar to our own: Some types of forgetting involve higher degrees of intentionality than do others. If our explanations of Bunting's (2006) data are accurate, we expect that individual differences in fluid intelligence would be more predictive of performance in tasks that Anderson listed as high in intentionality, relative to tasks lower in intentionality.

Verbal fluency—Working memory or fluid intelligence?

Due to the strong relation between working memory capacity and fluid intelligence, it is probable that at some point aspects of one ability have been falsely attributed to the other. We highlight this issue by juxtaposing a verbal fluency study by Rosen and Engle (1997) against recent data collected by Shipstead et al. (2015).

Verbal fluency tasks (Thurstone, 1938) require test takers to produce as many different cue-relevant exemplars as possible within a limited time frame—for instance, "words that start with 'C'" or "professions." Given the specificity of the cue, the main sources of interference are readily implicated as (a) already-recalled information that a test taker might resample (Azuma, 2004; Raboutet et al., 2010; Rosen & Engle, 1997) and (b) semantic clusters in which a test taker might perseverate (Troyer, Moscovitch, & Winocur, 1997; Unsworth, Spillers, & Brewer, 2011).

Rosen and Engle (1997) found that people with high working memory capacity outperformed those with low working memory capacity on verbal fluency tasks. Moreover, this effect was not attributable to categorical knowledge, since differences related to working memory capacity were apparent within the first minute of task performance (see also Unsworth et al., 2011). Instead, the difference was attributed to the tendency of individuals with low working memory capacity to return to already-retrieved responses, thus resulting in greater resampling (see Experiment 4 of Rosen & Engle, 1997).
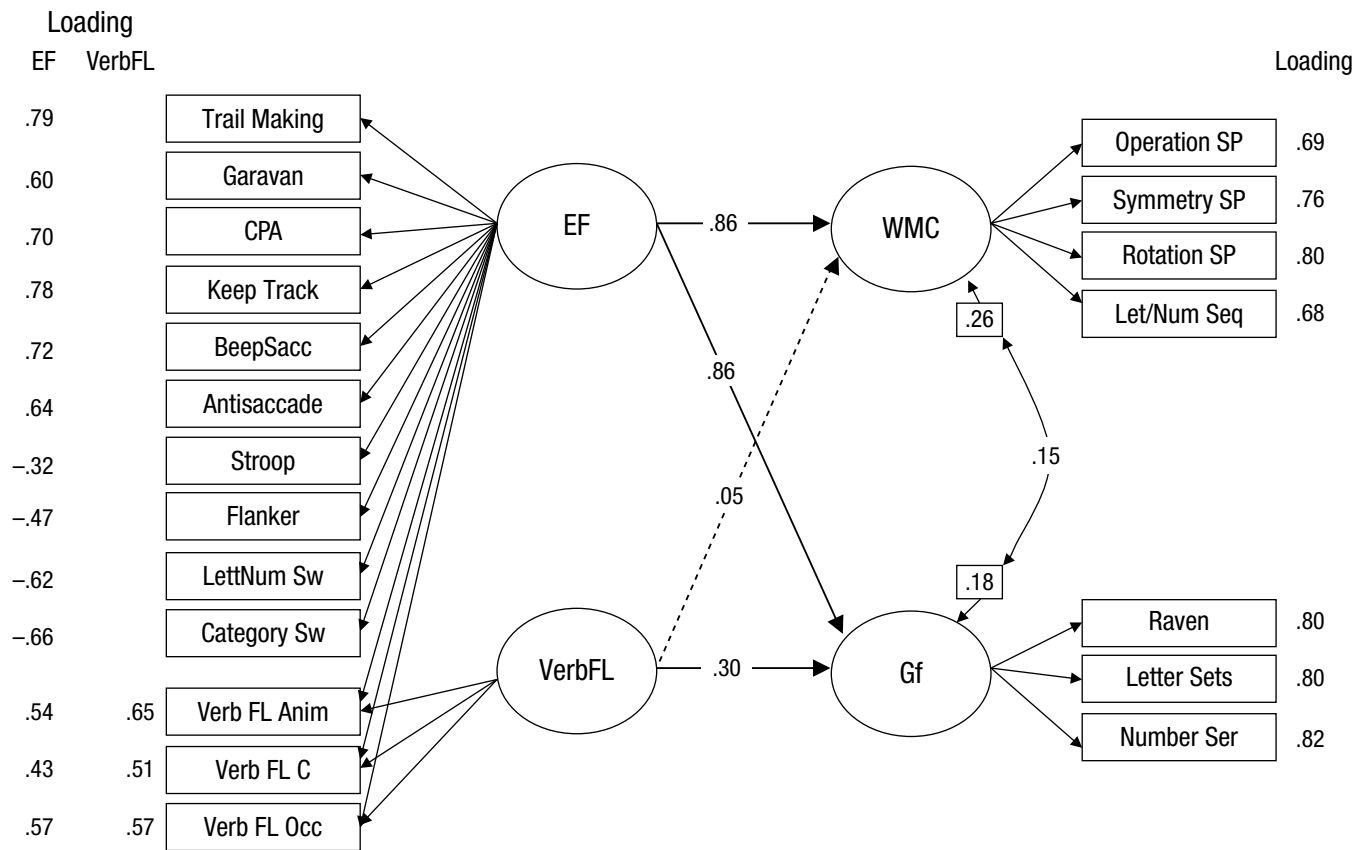
Fig. 14. The relations among executive function (EF), verbal fluency (VerbFL), working memory capacity (working memory capacity), and fluid intelligence (Gf). CPA = continuous paired associates; BeepSacc = antisaccade with beep; LettNum SW = letter number task switching; Anim = animal; C = words that start with C; Occ = occupations; SP = span; Seq = sequence; Ser =series. Fit statistics: χ^2= 517.93, degrees of freedom = 164, root mean square error of approximation = .06, standardized root mean square residual = .04, nonnormed fit index = .98, comparative fit index = .98.

However, a recently collected data set (Shipstead et al., 2015) suggests that Rosen and Engle (1997) made a misattribution. Shipstead et al. examined the relation among executive functions, working memory capacity, and fluid intelligence. Additionally, this study collected verbal fluency data.

Figure 14 presents a simplified version of the results.[11] In this structural equation model, factors are created by extracting variance common to several tasks and then the factors are related using latent regression. The factor labeled *EF* is a measure of executive function, created with the type of tasks that are often used in studies by Miyake and colleagues to measure individual executive functions (see Miyake & Friedman, 2012; Miyake et al., 2000), along with three verbal fluency tasks. Thus, this factor is similar to the concept of the central executive (Baddeley, 1986; Level 1 from Fig. 2), in that it represents variance that is common to many behaviors that require executive control. The factor labeled *VerbFL* is variance that is unique to verbal fluency tasks once any influence of general executive function has been removed.

The model in Figure 14 shows that executive functioning is strongly related to both working memory capacity (see also D. P. McCabe et al., 2010) and to fluid intelligence. This is not particularly surprising to us, given that an organizing executive signal is an important component of our model (e.g., the top portion of our theoretical model from Fig. 2). However, VerbFL has a significant relation to Gf but not to WMC (Fig. 14). In other words, once the influence of general executive functioning has been removed from verbal fluency performance, this variable is unrelated to working memory capacity. The unique aspects of verbal fluency are specifically related to fluid intelligence.

The relation of verbal fluency to fluid intelligence is more curious than it might seem at first glance. Verbal fluency is a solidly verbal factor. Fluid intelligence tasks—and the factor they typically form—are confounded with visuospatial memory, due to the mode of presentation (Kane et al., 2004). Unless fluid intelligence factors are strictly defined by verbal reasoning tasks, they will have little relation to verbal memory factors (Kane et al., 2004).

Why then should VerbFl and Gf (Fig. 14) have a special relation?

People who are high in verbal fluency produce many different responses to a cue. Key to this action is the ability to avoid returning to already-recalled responses (Azuma, 2004; Raboutet et al., 2010; Rosen & Engle, 1997) and to move beyond semantic clusters that have been exhausted (Troyer et al., 1997; Unsworth et al., 2011). Executive functioning facilitates these actions by resolving competition for retrieval into the focus of attention and by carrying out retrieval strategies (see Raboutet et al., 2010). However, executive attention does not fully explain these actions, as evidenced by the residual verbal fluency factor.

We attribute this relation to the ability to disengage from outdated information and hypothesize that research in previous studies in which verbal fluency-related disengagement was attributed to working memory capacity suffered from two issues. First, fluid intelligence was not measured by Rosen and Engle (1997; see also Unsworth et al., 2011). Given the strength of the latent relation between working memory capacity and fluid intelligence (in Fig. 14, $r = .88$), working memory capacity tasks can be deemed low-grade fluid intelligence tasks and vice versa (e.g., Figs. 12 and 13). Experiments like those of Rosen and Engle (1997) create a third-variable problem in which the relation of working memory capacity to verbal fluency cannot be examined apart from a common relation to fluid intelligence.

Second, the use of extreme-groups design (i.e., only including people who are very high or very low in working memory capacity) exacerbates this issue. Obvious criticisms of such designs include the fact that the middle portion of a distribution is treated as continuous and therefore effect sizes are inflated because only extreme cases are examined. However, we see an even greater reason to interpret these studies cautiously: Being high in working memory capacity likely means being high in fluid intelligence. Therefore, the likelihood that working memory capacity will serve as a stand-in for fluid intelligence is increased, and outcomes will be falsely attributed to individual differences in working memory capacity (or vice versa) when researchers fail to measure both variables.

Familiarity, recollection, and n-back performance

One relevant concern regards the roles of familiarity and recollection in memory task performance. *Familiarity* is a sense that information has been seen before, whereas *recollection* is the ability to remember information in its proper context. The first process functions automatically; the second requires cognitive control (Jacoby, 1991). To make clear the familiarity/recollection distinction in terms of traditional views of working memory (e.g., Cowan, 1999, 2001), one could think of temporarily retained information in focal attention as a mechanism of recollection, while passive memories of older items could be seen as a type of familiarity. Such perspectives might assume that due to their relatively small storage capacities, people of lower cognitive ability are prone to using the sense of familiarity as a method of remembering over the short term.

In terms of the *n*-back study, if people with small storage capacities can maintain only two items in the focus of attention, then a 3-back task would be more than they can reasonably handle. They therefore would be prone to responding on the basis of the sensation that they have seen an item before. This response could account for their tendency to register false alarms at basically the same rate across all *n*-back positions.

Although this perspective is sensible, it is curious that lure accuracy could not be attributed to individual differences in working memory capacity, since storage capacity is ostensibly the deficient mechanism. Why should lure performance be attributable to fluid intelligence if the limitation is working memory storage?

Moreover, the familiarity/recollection explanation does not readily eliminate the utility of disengagement processes. People of higher cognitive ability show gradual reductions in proneness to false alarms, indicating that the need to disengage from maintained information is important—at least for people with larger storage capacities.

Perhaps, disengagement only applies to individuals with memory capacities high enough to allow for recollective responding. This is a somewhat different perspective than ours, although there is an important commonality. Namely, the memory issues of people of lower cognitive ability arise, in part, because these people are overrun by irrelevant information that cannot be placed in its correct context. Therefore, the main points of our discussion are not necessarily incompatible with fixed-capacity models.

The (non?) distinction among storage capacity, working memory capacity, and fluid intelligence

Our classic depiction of working memory capacity is summarized as "working memory capacity = short-term storage capacity + executive attention" (Engle, Tuholski, Laughlin, & Conway, 1999). The idea is that short-term storage capacity represents the amount of information that a person can store passively. The term *working memory capacity* is applied when that person engages attention to actively prevent stored information from being forgotten.

By this logic, converting the operation span (see Fig. 1a) into a short-term storage task seems straightforward: remove the interpolated processing task (Daneman & Carpenter, 1980; Engle & Oransky, 1999; Engle et al., 1999). Without the distraction, there would be less need to engage executive attention, and the task would primarily measure storage capacity.

Roberto Colom and colleagues (Colom et al., 2008; Colom, Abad, Rebollo, & Shih, 2005; Colom et al., 2004; Martínez et al., 2011) have challenged this perspective via demonstrations that (a) at the level of latent analysis, there is not much difference between individual differences in performance of simple and complex span tasks and (b) neither of the factors underlying these tasks is very different from general intelligence. A common interpretation of such findings has been to conclude that storage capacity is the common component underlying simple span, complex span, and general intelligence (Colom et al., 2008; Colom et al., 2005; for similar perspectives with different tasks, see also Chuderski et al., 2012; Cowan et al., 2005).

Indeed, there is a great deal of similarity in the cognitive components that are measured by complex and simple span tasks (e.g., Kane et al., 2004; Unsworth & Engle, 2007b), and our perspective on working memory capacity has evolved along with such data. However, our response has been to de-emphasize the storage component of working memory in favor of emphasizing the role of active processing that keeps attention focused on relevant memories (Shipstead & Engle, 2013; Shipstead et al., 2015; Shipstead et al., 2014).[12] In essence, scores on "storage" tasks can also be explained through a person's ability to remain focused on the task at hand. People who are focused produce higher scores on memory tasks. People who are unfocused produce lower scores. Thus, we attribute common variance to the executive component of working memory (Level 1; Fig. 2).[13]

Turning to reasoning ability, the general consensus seems to be that working memory capacity and fluid intelligence are at least distinguishable (Ackerman et al., 2005; Kane et al., 2005; Oberauer et al., 2005). Contrary to this position, Colom and colleagues have pointed to several cases in which correlations between working memory capacity and intelligence factors are approaching 1.0 (Colom et al., 2008; Colom et al., 2005; Colom et al., 2004; Martínez et al., 2011).

Our take on such findings is that we can distinguish between working memory capacity and fluid intelligence much as we can distinguish two sides of a coin. They are inextricably tied together, and therefore latent correlational models sometimes approach unity. At the same time, there are differences. The best way to understand these constructs is not simply to explore how they are the same but also to ask how they are different. It is important to note that the present data indicate that individual differences in fluid intelligence predict the ability to put outdated information out of mind—in a way that working memory capacity is insufficient to explain.

Working memory training and fluid intelligence

We have a history of skepticism toward the field of working memory training, particularly toward the idea that fluid intelligence increases after a few hours of practice on memory tests (Harrison et al., 2013; Redick et al., 2013; Shipstead, Hicks, & Engle, 2012a, 2012b; Shipstead et al., 2010; Shipstead, Redick, & Engle, 2012). However, our current perspective offers new ways of approaching cognitive training—in particular, theoretical expectations of posttraining transfer between working memory capacity and fluid intelligence.

Does the present perspective allow for the possibility that training working memory capacity can improve fluid intelligence? Although we do not treat maintenance ability as the primary determinant of a person's fluid intelligence, we do acknowledge that some people with low fluid intelligence may test that way because they simply lack the basic capacity to properly represent fluid intelligence problems.

Therefore, if a cognitive training method were truly effective at improving working memory, people with lower working memory capacity would benefit in ways that could also improve fluid intelligence. Indeed, Jaeggi et al. (2008) noted a trend in their data that showed people with lower cognitive abilities experienced larger posttest increases in fluid intelligence, relative to the people in the upper half of a median split. Unfortunately, because the groups were formed on the basis of pretest scores, these data are confounded with regression to the mean (Campbell & Stanley, 1963). The point stands, nonetheless: Although we believe that increasing working memory capacity does not necessitate an increase in fluid intelligence (Harrison et al., 2013), it is quite plausible that people with very poor maintenance abilities could benefit from training in broad ways.

We have argued elsewhere that *n*-back training shows the most promise as a method of increasing fluid intelligence (Shipstead et al., 2010). However, reports of posttraining increases in fluid intelligence thus far have contended with a very real problem: *n*-back training does not increase working memory capacity (Shipstead, Redick, & Engle, 2012).

This is problematic from any perspective that assumes working memory capacity to be the primary limiting factor of a person's fluid intelligence. Why should fluid

intelligence increase when working memory does not (Shipstead, Redick, & Engle, 2012)? After all, increased working memory capacity is the ostensible mechanism through which cognitive change is explained. Does this mean that studies that report improved fluid intelligence in the absence of increase working memory capacity are simply reporting noise (Shipstead, Redick, & Engle, 2012)?

From the present perspective, these trends are not theoretically problematic if *n*-back training primarily increases disengagement ability. If working memory capacity tasks primarily tap into maintenance processes, then improving disengagement processes may only increase working memory capacity for people who are so overrun by proactive interference that active maintenance cannot function properly. For the general population, a training task that improves disengagement ability could conceivably increase fluid intelligence without affecting working memory capacity.

At this point, there does seem to be a weak effect of *n*-back training on improved performance of fluid intelligence tasks (although we note that this effect is not apparent in studies with tight controls; see Au et al., 2015). If this effect does represent increased fluid intelligence, can we increase the effect size? The present research presents an avenue for researching this goal.

In the typical adaptive *n*-back task (e.g., Jaeggi et al., 2011), researchers alter difficulty by moving the target item farther back in time (e.g., 3-back, then 4-back, then 5-back). The supposition is that this action will strain maintenance capacity and therefore improve working memory. Because *n*-back training does not increase working memory capacity (Redick et al., 2013; Shipstead, Redick, & Engle, 2012), this idea has been not borne out.

Yet it is possible that people gradually need to deal with interference from farther back in time, and thus something that is critical to performing fluid intelligence tasks is being trained. Unfortunately, most training studies do not directly manipulate the presence of lure items as we did in our study (but see Persson & Reuter-Lorenz, 2008, 2011). At this point, it would seem that given the need to increase the size of the fluid intelligence training effect, a worthwhile avenue to explore is the direct manipulation of interference, particularly at distant periods.

While we encourage continued research in the area of cognitive training, we remain skeptical of its present applicability. Cognitive abilities develop over a lifetime and after years of complex interaction with the environment (see Nisbett, 2009). One year of school is associated with, at most, 2.7 IQ points (Winship & Korenman, 1997). It may well be asking far too much of a task to expect it to improve fluid intelligence after a few hours of practice.

Summary and Concluding Remarks

Cognitive psychology has a standing interest in explaining human reasoning from a mechanistic perspective. Some researchers argue that this is most readily accomplished by uncovering the mechanisms that explain individual differences in the seemingly tractable concept of working memory capacity (Conway, Getz, Macnamara, & Engel de Abreu, 2010; Oberauer et al., 2007; Shipstead et al., 2014; Unsworth et al., 2014). Although we see benefit in this approach (see Shipstead et al., 2014) we also believe that much can be learned by recognizing that reasoning is not the same thing as working memory capacity (Ackerman et al., 2005). It is important that we also explore how these concepts are different.

In particular, intentional forgetting seems to explain aspects of complex thought apart from working memory. However, there are obvious shortcomings of our approach. First, there is probably no process-pure operationalization of either maintenance or disengagement. One cannot update memory if information is not maintained. Similarly, maintenance capacity is diminished by the presence of outdated information (Keppel & Underwood, 1962; Shipstead & Engle, 2013; Souza & Oberauer, 2015; Wickens et al., 1963). As such, a clean dissociation (e.g., Jacoby, 1991) between these processes is unlikely.

Second, it is important to remember that we are studying individual differences variables. People cannot be assigned to be high or low in fluid intelligence. Correlational studies can produce data that are in line (or out of line) with our theory, but they cannot uncover the chain of events that lead to a problem being solved. Therefore, it will be difficult to establish that intentional forgetting causally affects a person's ability to reason through problems.

At the same time, the idea that the ability to forget outdated ideas allows one to generate new ideas has an unexpectedly intuitive appeal and is backed by our data and the data of others (e.g., Colom et al., 2008; Jarosz et al., 2012; Storm & Angello, 2010; DeCaro, Van Stockum, & Wieth, 2015). It should be noted that this idea also points to shortcomings in our theorizing about working memory. In general, researchers focus on the importance of maintenance (Chuderski et al., 2012; Cowan, 2001; Engle, 2002) but set aside the study of other mechanisms that allow for cognitive flexibility. In our view, future theories in this area need to emphasize not only the processes that allow people to represent the present but also those that allow them to move beyond the recent past.

Appendix

Method

Participants, procedure, and data preparation

The present data were drawn from pool of 573 college students and members of the Atlanta (Georgia) and Columbus (Indiana) communities. All participants completed an extensive four-session screening procedure that is detailed in Shipstead et al. (2015). All sessions were completed on separate days and included between one and five people working at partition-separated computers. Average time to completion was 20.55 days. Because large portions of these data were collected for the purposes of structural equation modeling, the order in which tasks were presented was fixed so as to avoid subject-by-treatment interactions.

Six different *n*-back tasks were performed (detailed in a later section). Lures are defined as items that had been previously presented but not three items back. In half the tasks, lures were distant, and in half, lures were near. Distant lure *n*-back tasks presented lure items in the 7-, 8-, or 9-back positions. Near lure n-back tasks presented lure items in the 2-, 4-, and 5-back positions. Among numerous other tasks, two *n*-back tasks were performed at each of the first three sessions. A distant lure *n*-back with words and a distant lure *n*-back with faces were performed at the first session. A distant lure *n*-back with wingding items and a near lure *n*-back with words were performed at the second session. A near lure *n*-back with faces and a near lure *n*-back with wingding items were performed at the third session. In order to avoid item-specific effects, we used the same items in both distant and near tasks. Therefore, distant lure tasks were performed first to ensure that proactive interference from previous tasks would not affect performance (although given that 37 tasks were performed across the first three sessions, this possibility was likely minimized).

For all *n*-back tasks, participants were required to make a yes/no judgment as to whether an item was in the 3-back position. Items were presented at a rate of one every 2 s, regardless of whether or not a response was being made. Only trials in which a response was made were included in the analysis. Of all participants, 39 did not make enough valid responses on at least one of the six *n*-back tasks for us to calculate d′ for at least one of the lure position. Whether this was due to the participants' misunderstanding the instructions or to their failure to follow instructions, these data were missing for nonrandom purposes. Thus, these participants were removed from all analyses, leaving a final sample of 534. Any missing data for working memory capacity and fluid intelligence tasks were attributable to computer malfunction and thus deemed random. These missing points were imputed using the expectation–maximization (EM) procedure in EQS software. *Z*-score composites were then created for working memory capacity and fluid intelligence.

Tasks

Working memory capacity. Three of the four working memory tasks were complex span tasks, in which test takers must recall a series of serially presented items, the presentation of which is interrupted by a simple processing task. For these tasks, the dependent variable was the number of to-be-remembered items recalled in proper serial position. The only task that did not follow this procedure was letter-number sequencing.

Automated operation span (OSpan; Unsworth, Heitz, Schrock, Engle, 2005). The to-be-remembered items are letters from the alphabet. The processing task involved simple mathematical equations were solved before the next letter of a sequence was presented. Lists lengths varied between three and seven items.

Automated symmetry span (SymSpan; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). The to-be-remembered items were separate spatial locations on a 4 × 4 grid. The processing task involved judging whether or not a figure in an 8 × 8 grid was symmetrical. List lengths ranged between two and five items.

Automated rotation span (RotSpan; Harrison et al., 2013). The to-be-remembered items were a sequence of long and short arrows that radiated from a central point. The processing task required test takers to judge whether a rotated letter was forward facing, or mirror-reversed. List lengths ranged between two and five items.

Letter-number-sequencing (LNS; Emery, Myerson, & Hale, 2007). LNS presented a sequence of digits and letters (e.g., 3, T, 1, R). At the end of the sequence, the test taker first recalled the digits in ascending order (1, 3), then the letters in alphabetical order (R, T). The first sequence was two items (one letter, one number). Participants performed a block of three trials of this length. If test takers recalled at least one list correctly, then they were given three more trials, this time with lists that were one item longer. Testing ended when either (a) the test taker could not recall one list from a block or (b) the test taker completed a block of nine-item lists. The dependent variable was the number of lists that were correctly recalled.

General fluid intelligence. For all fluid intelligence tasks, the dependent variable was the number of correct responses provided within the allotted time.

Raven's Advanced Progressive Matrices (Raven; Raven, 1990; Odd problems). On each trial, eight abstract figures were embedded in a 3×3 matrix (similar to Fig. 1b). The final position in the matrix was blank. Test takers select one of several options completed the sequence. They were given 10 min to solve 18 problems.

Letter sets (LetterSet; Ekstrom et al.,1976). Five four-letter strings were presented. All but one set followed a specific rule. The test taker needed to discern this rule and select the string did not follow it. The test taker was given 7 min to complete 30 problems.

Number series (NumSer; Thurstone, 1938). A series of numbers that were joined by a rule were presented on a computer screen. The test taker needed to discern this rule and decide which number was next in the sequence. The test taker was given 5 min to complete 15 problems.

N-back. As stated earlier, there were six *n*-back tasks. Two used Chinese faces (from Gao et al., 2008), two used words, and two used wingding font items as the to-be-remembered stimuli. For each variety of stimuli, one task had lures in positions 2-, 4-, or 5-back and one had lures at positions 7-, 8-, or 9-back.

In each task, there were 10 targets, 10 lures for each position, and 10 filler items that never repeated. The sequence of events and the role of an item as a target or lure were prerandomized. To familiarize participants with the task, we conducted several practice trials in which key presses were required to advance the stimuli, along with a block of 40 practice trials that follow the timing sequence detailed in the following.

Each stimulus was presented for up to 2,000 ms with a 500-ms pause. Stimuli disappeared when a response was made, but this did not affect the stimulus-to-stimulus timing. The dependent variables were hits, false alarms, and d′, which was calculated using hits at the 3-back position and false alarms at each of the lure positions (2, 4, 5, 7, 8, and 9). Otherwise, the specifics of our d′ calculation matched those of Kane, Conway, Miura, & Colflesh (2007).

Results

Analysis of d′. A main effect of lure position indicated that d′ increased as lures became more distant in time, $F(5, 2665) = 237.16$, $MSE = 223.88$, $p < .001$, $\eta^2_p = .31$. We tested interactions with fluid intelligence and working memory capacity separately using median splits of the composite scores. In both cases, people with high and low fluid intelligence, $F(5, 2660) = 13.78$, $MSE = 13.78$, $p < 001.$, $\eta^2_p = .03$, and working memory capacity, $F(5, 2660) = 11.91$, $MSE = 11.02$, $p < 001.$, $\eta^2_p = .02$, diverged in terms of d′ as the lures became more distant. In both

cases, tests of quadratic contrasts failed to reach significance (respectively, *p*s =.23 and .91), indicating that differences were smallest at near-lure positions and steadily increased across farther positions.

Analysis of hits. A main effect of lure distance indicated that people had a higher proportion of hits on *n*-back tasks that featured distant lures (.54) than on tasks that featured near lures (.39), $F(1, 533) = 445.40$, $MSE = 5.66$, $p < .001$, $\eta^2_p = .46$. There were also main effects of fluid intelligence, $F(1, 532) = 444.57$, $MSE = 5.66$, $p < .001$, $\eta^2_p = .46$, and working memory capacity, $F(1, 532) = 445.04$, $MSE = 5.66$, $p < .001$, $\eta^2_p = .46$, though interactions did not obtain (respectively, $p = .99$ and .45).

Analysis of false alarms. A main effect of lure position indicated that false alarms decreased as lures became more distant, $F(5, 2665) = 34.47$, $MSE = .34$, $p < .001$, $\eta^2_p = .06$; however, as indicated by Figure 7, there was an increase between Position 5 and Position 7, likely due to Position 5 being relatively distant in the near lure tasks and Position 7 being relatively near in the distant lure tasks. Consistent with the discussion in the main text, interactions obtained between lure position and both fluid intelligence, $F(5, 2660) = 35.82$, $MSE = .21$, $p < .001$, $\eta^2_p = .04$, and working memory capacity, $F(5, 2660) = 20.57$, $MSE = .19$, $p < .001$, $\eta^2_p = .04$.

Notes

1. Disengagement refers to the act of unbinding no-longer-relevant information from attention. This may be driven by mechanisms such as inhibition of outdated information (e.g., Storm, 2011) or episodic memory that certain information is irrelevant (Neill & Valdes, 1996). We use *disengagement* as an agnostic term that may represent either or both accounts.

2. For examples of the negative effects that maintenance can have on retrieval, see Raaijmakers and Shiffrin (1981).

3. Note that we do not necessarily see active suppression as a mechanism of disengagement, and there are also alternate

theories of the type of forgetting studied by Storm and Angello (2010) that do not rely on suppression (see Storm, 2011).

4. A strengthening of the correlation to working memory capacity specifically occurred when a short intertrial interval was paired with a long retention interval. This is when proactive interference was maximized and likely has more to do with difficulty of retrieval with than disengagement. We predicted this outcome on the basis of the findings in Unsworth and Engle (2007a).

5. Note that these data were collected as part of a large screening procedure (Shipstead et al., 2015) but have not been reported elsewhere. Methods can be found in the Appendix.

6. The trend was similar for working memory capacity; however, subsequent analyses will attribute this to fluid intelligence. Therefore, working memory capacity was omitted from the figure for visual clarity.

7. Note that the increase in false alarms from Positions 5 to 7 is likely an artifact of the method of testing, in which 5 was the most distant lure position for half of the n-back tasks and 7 was the closest lure position for the other half of the tasks.

8. Although a p value of .06 is far too low for us to conclude a lack of a relation, the large sample size does suggest that a traditionally powered study would be unlikely to produce a reliable correlation.

9. In effect, we are extending known retrieval-based issues to active maintenance (see Raaijmakers & Shiffrin, 1981; Wixted & Rohrer, 1994).

10. "[T]he dependence of lower-stratum abilities on higher-stratum abilities is indicated by their loadings on them" (Carroll, 1993, p. 636).

11. Note that although this model uses data reported by Shipstead et al. (2015), it does not appear in the referenced study. The correlation matrix will be made available on the third author's website (http://englelab.gatech.edu/) upon publication of Shipstead, Harrison et al.

12. Martínez et al. (2011) introduced a somewhat more process-driven perspective. Along with our own movement toward an integrated view of working memory capacity and storage capacity, our perspectives may be less divergent than they sometimes seem (e.g. Engle et al. 1999 vs. Colom et al., 2008).

13. Instead of arguing that simple span tasks are measuring something that is of little importance to higher cognition (e.g., Daneman & Carpenter, 1980; Engle et al., 1999), we assume that these tasks are simply relatively inconsistent measures of the processes that define working memory capacity (see Unsworth & Engle, 2007a).

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