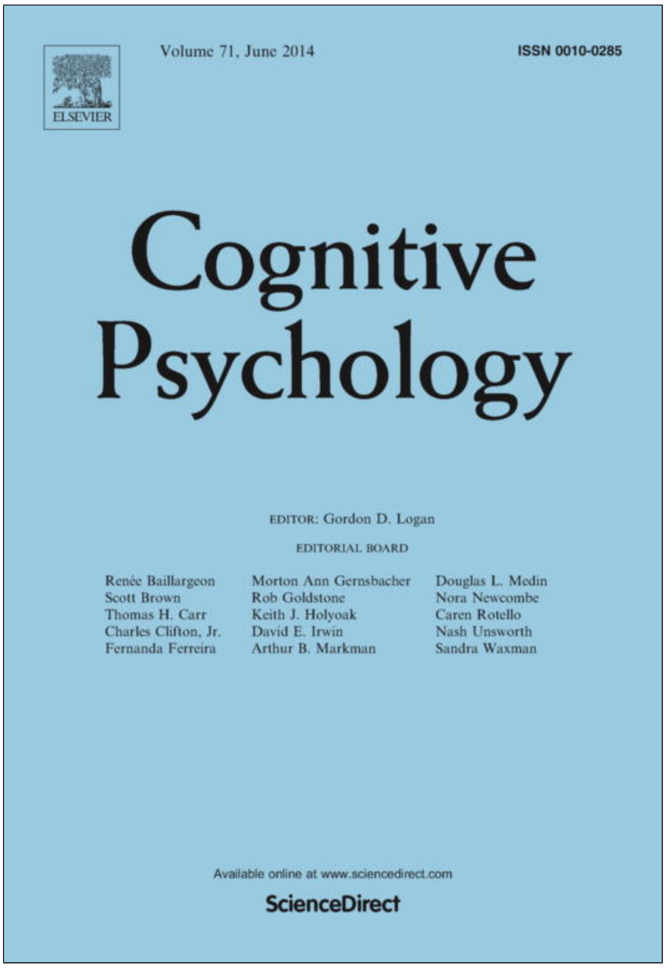
Volume 71, June 2014
ISSN 0010-0285
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Cognitive Psychology 71 (2014) 1–26

Contents lists available at ScienceDirect

Cognitive Psychology

journal homepage: www.elsevier.com/locate/cogpsych

Working memory and fluid intelligence: Capacity, attention control, and secondary memory retrieval

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ARTICLE INFO

Article history:
Accepted 22 January 2014
Available online 14 February 2014

Keywords:
Working memory
Fluid intelligence

ABSTRACT

Several theories have been put forth to explain the relation between working memory (WM) and gF. Unfortunately, no single factor has been shown to fully account for the relation between these two important constructs. In the current study we tested whether multiple factors (capacity, attention control, and secondary memory) would collectively account for the relation. A large number of participants performed multiple measures of each construct and latent variable analyses were used to examine the data. The results demonstrated that capacity, attention control, and secondary memory were uniquely related to WM storage, WM processing, and gF. Importantly, the three factors completely accounted for the relation between WM (both processing and storage) and gF. Thus, although storage and processing make independent contributions to gF, both of these contributions are accounted for by variation in capacity, attention control and secondary memory. These results are consistent with the multifaceted view of WM, suggesting that individual differences in capacity, attention control, and secondary memory jointly account for individual differences in WM and its relation with gF.

1. Introduction

Complex working memory (WM) span tasks such as reading and operation span have been shown to be important predictors of a number of higher-order and lower-order cognitive processes. In these

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http://dx.doi.org/10.1016/j.cogpsych.2014.01.003
0010-0285/

tasks to-be-remembered items are interspersed with some form of distracting activity such as reading sentences or solving math problems. Based on these complex span tasks, WM has been shown to predict performance on a number of higher-order cognitive tasks including reading comprehension (Daneman & Carpenter, 1980), vocabulary learning (Daneman & Green, 1986), and performance on the SATs (Turner & Engle, 1989). Likewise, WM span tasks have been shown to predict performance on a number of attention and inhibition tasks (Engle & Kane, 2004; McVay & Kane, 2012; Unsworth & Spillers, 2010a), as well as predict performance on a number of secondary or long-term memory tasks (Unsworth, 2010; Unsworth, Brewer, & Spillers, 2009). Furthermore, these tasks have been shown to predict important phenomena such as early onset Alzheimer's (Rosen, Bergeson, Putnam, Harwell, & Sunderland, 2002), life-event stress (Klein & Boals, 2001), aspects of personality (Unsworth, Miller, Lakey, Young, Meeks & Campbell, 2009), susceptibility to choking under pressure (Beilock & Carr, 2005), and stereotype threat (Schamader & Johns, 2003).

It is clear from a number of studies that WM has substantial predictive power in terms of predicting performance on a number of measures. In particular, the relation between WM and fluid intelligence has received a considerable amount of attention. Fluid intelligence (gF), which is the ability to solve novel reasoning problems, has been extensively researched and shown to correlate with a number of important skills such as comprehension, problem solving, and learning (Cattell, 1971), and has been found to be an important predictor of a number of real world behaviors including performance in educational settings (Deary, Strand, Smith, & Fernandes, 2007) as well as overall health and mortality (Gottfredson & Deary, 2004). Beginning with the work of Kyllonen and Christal (1990) research has suggested that there is a strong link between individual differences in WM and gF. In particular, this work suggests that at an individual task level measures of WM correlate with gF measures around .45 (Ackerman, Beier, & Boyle, 2005) and at the latent level WM and gF are correlated around .72 (Kane, Hambrick, & Conway, 2005). Thus, at a latent level WM and gF seem to share approximately half of their variance. However, the reason for this predictive power remains elusive. The current study examines the extent to which multiple factors (capacity, attention control, and secondary memory) rather than a single factor account for the relation between WM and gF.

Closely following the ideas of Baddeley and Hitch (1974), one of the first theories put forth to explain individual differences in WM and its relation with higher-order cognition suggested that individuals have a fixed pool of resources which they can allocate to both processing and storage in complex span tasks. In this view complex span tasks measure the dynamic tradeoff between processing and storage and that as the processing component becomes more taxing, there are fewer resources left over to store the to-be-remembered (TBR) items (Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Daneman & Tardif, 1987; Just & Carpenter, 1992). Thus, the storage score provides an index of how efficiently an individual can process and store information. If a person can efficiently process a lot of information then there will be adequate resources available for storage and hence a high storage score. However, if a person is less efficient at processing information, most of their resources will be devoted to the processing task, leaving few resources available for storage and hence a low storage score. Furthermore, this view argues that the reason WM (as measured by complex span tasks) predicts higher-order cognition so well is because WM represents the dynamic tradeoff between processing and storage which is needed in many complex cognitive tasks including measures of gF. As such, resource sharing is thought to underlie individual differences in WM and account for their relation with higher-order cognition. Problems with resource sharing views are findings that processing and storage can make independent contributions to task performance and to the correlation with measures of mental abilities (Bayliss, Jarrold, Gunn, & Baddeley, 2003; Duff & Logie, 2001; Logie & Duff, 2007; Unsworth, Redick, Heitz, Broadway & Engle, 2009; Waters & Caplan, 1996). That is, although prior work has shown that measures of processing are in fact related to measures of higher-order cognition including measures of gF, WM storage scores still predicted higher-order cognition even after controlling for processing (Bayliss et al., 2003; Engle, Cantor, & Carullo, 1992; Friedman & Miyake, 2004; Unsworth, Heitz, Schrock, & Engle, 2005; Unsworth, Redick, et al., 2009). Thus, although the relation between processing and storage is important, prior research has demonstrated that variation in processing efficiency or resource sharing does not fully account for the relation between WM (particularly WM storage) and gF.

More recent theories of WM have moved away from the idea that resource sharing between processing and storage is what is important, and have instead proposed that individual differences in WM are due to something else. For example, one popular theory that has been put forth to explain the relation between WM and gF is that individual differences in WM largely reflect differences in attention control (Engle & Kane, 2004). Attention control theories suggest that domain general attention control abilities are needed to actively maintain task relevant information in the presence of potent internal and external distraction. Thus, attention control (similar to inhibitory control) is needed to maintain information in an active state and to block and inhibit irrelevant representations from gaining access to WM. According to attention control views of WM, high WM individuals have greater attention control and inhibitory capabilities than low WM individuals, and thus are better at actively maintaining information in the presence of distraction. Evidence consistent with this view comes from a number of studies which have found strong correlations between various attention control measures and WM and both the task and latent levels (Engle & Kane, 2004; McVay & Kane, 2012; Unsworth & Spillers, 2010a). In terms of predicting gF, attention control views have specifically suggested that the reason that WM and gF are so highly related is because of individual differences in attention control. Recent research has demonstrated that attention control is strongly related with gF, and partially mediates the relation between WM and gF (Unsworth & Spillers, 2010a; Unsworth, Spillers, & Brewer, 2009). However, in these prior studies WM still predicted gF even after accounting for attention control, suggesting that attention control is not the sole reason for the relation between WM and gF.

In contrast to attention control views, recent work has suggested that individual differences in WM are primarily due to capacity limits in the number of things that participants can maintain in WM (Cowan et al., 2005; Unsworth, Spillers, & Brewer, 2010). Theoretically, the number of items that can be maintained is limited to roughly four items but there are large individual differences in this capacity (Awh, Barton, & Vogel, 2007; Cowan, 2001; Cowan et al., 2005; Luck & Vogel, 1997; Vogel & Awh, 2008). Thus, individuals with large capacities can simultaneously maintain more information in WM than individuals with smaller capacities. In terms of gF, this means that high capacity individuals can simultaneously attend to multiple goals, sub-goals, hypotheses, and partial solutions for problems which they are working on allowing them to better solve the problem than low capacity individuals who cannot maintain/store as much information. Evidence consistent with this hypothesis comes from a variety of studies which have shown that capacity measures of WM are correlated with complex span measures of WM and with gF (Cowan, Fristoe, Elliot, Brunner, & Saults, 2006; Cowan et al., 2005; Fukuda, Vogel, Mayr, & Awh, 2010; Shipstead, Redick, Hicks, & Engle, 2012). However, like the results from examining attention control theories, recent research has found that WM still predicted gF even after accounting for the number of items that individuals can maintain (Shipstead et al., 2012). Thus, individual differences in the number of items that can be maintained only partially mediates the relation between WM and gF.

Given that capacity is limited to approximately four items, and given that attention control abilities are limited in the extent to which they can protect items from distraction, it seems likely that some items will not be able to be maintained and thus, they will have to be retrieved from secondary memory (or long-term memory). In this view it is suggested that individual differences in WM are partially due to differences in the ability to retrieve items from secondary memory that could not be actively maintained (Unsworth & Engle, 2007a). Specifically, this view suggests that high WM individuals are better at controlled search abilities than low WM individuals. These controlled search abilities include setting up an overall retrieval plan, generating retrieval cues to search memory with, and various monitoring decisions. Evidence consistent with this view comes from a number of studies which has demonstrated a strong link between WM measures and secondary memory measures (Unsworth, 2010; Unsworth, Brewer, et al., 2009). In terms of gF, this view suggests that part of the reason that WM and gF correlate so well is because both rely, in part, on secondary memory retrieval. That is, high WM individuals are better able to solve reasoning problems than low WM individuals because even though some information (goals, hypotheses, partial solutions, etc.) will be displaced from the focus of attention, high WM individuals will be better at recovering that information and bringing it back into the focus of attention than low WM individuals. Likewise, Ericsson and Kintsch's (1995; see also Ericsson & Delaney, 1999) long-term working memory model suggests that variation in WM is due to differences in the ability to encode information into secondary or long-term memory and to use retrieval cues to rapidly access important information. Furthermore, these long-term working memory skills, rather than differences in capacity or attention control, are what account for the relation between WM and higher-order cognition (Ericsson & Delaney, 1999). A number of recent studies have provided evidence consistent with these view by demonstrating that WM and secondary memory measures are correlated, and both are correlated with gF (Mogle, Lovett, Stawski, & Sliwinski, 2008; Unsworth, 2010; Unsworth, Brewer, et al., 2009). Importantly, like the other theories, prior studies have found that individual differences in secondary memory only partially mediate the relation between WM and gF.

The work reviewed thus far suggests that there is likely not a single factor that accounts for the relation between WM and gF. Specifically, although attention control, capacity, and retrieval from secondary memory, were all found to account for some of the relation, none were found to fully account for the relation (see Unsworth, in press for a review). This suggests that the relation between WM and gF is multifaceted in that a number of processes are likely important. In prior work, one of us has suggested that WM is represented by both primary and secondary memory components (Unsworth & Engle, 2007a; Unsworth & Spillers, 2010a). Primary memory reflects both the number of items that can be distinctly maintained and attention control processes that actively maintain those items and prevent attentional capture. Secondary memory reflects the need to retrieve items that could not be maintained in primary memory as well as the need to retrieve other relevant information from secondary memory. According to this multifaceted model of WM, there are multiple sources of variance within WM measures, and multiple sources of variance that account for the relation between WM and gF (Unsworth, in press; Unsworth & Spillers, 2010a; Unsworth, Brewer, et al., 2009; see also Conway, Getz, Macnamara, & Engel de Abreu, 2011). Likewise, Cowan et al. (2006) suggested that both capacity and attention control would be important sources of variation.

The current study represents a direct test of this multifaceted view of WM and its relation to gF. In particular, although prior work has suggested that each of these factors (attention control, capacity, and secondary memory retrieval) are important, no study has simultaneously examined all three to determine if they will jointly mediate the relation between WM span and gF. As noted previously, WM always seems to have a residual relation with gF, even after controlling for other factors. However, this could be due to the fact that no prior study has jointly examined all three factors. In one prior study, both attention control and secondary memory were examined, but WM still predicted gF after controlling for these other two factors (Unsworth & Spillers, 2010a). This suggests that WM is composed of distinct processes and these processes independently contribute to individual differences in gF. If the multifaceted view of WM is correct, then we should see that WM is related to all three factors, all three factors are related to gF, and importantly all three factors mediate the relation between WM and gF, with little to no residual relation between WM and gF. Furthermore, given that in most prior studies the storage score from complex span tasks was used to index WM, we also examined measures of processing (specifically processing time) from the complex span tasks. As mentioned previously, prior work has suggested that WM represents resource sharing between processing and storage and it is this resource sharing ability that leads to variation in WM and accounts for its relation with higher-order cognition (Case et al., 1982; Daneman & Carpenter, 1980; Daneman & Tardif, 1987; Just & Carpenter, 1992). However, other research suggests that processing and storage make independent contributions to performance and to the relation with gF (Bayliss et al., 2003; Logie & Duff, 2007; Unsworth, Redick, et al., 2009; Waters & Caplan, 1996). Thus, it remains possible that processing along with storage accounts for the relation between WM and gF without the need for postulating other factors. It is also possible that the relations between both processing and storage with gF are accounted for by different contributions from attention control, capacity, and secondary memory. That is, both processing and storage might actually reflect independent contributions from attention control, capacity, and secondary memory.

To examine these notions we had a large number of participants perform multiple complex span, attention control, capacity, secondary memory, and gF tasks and we used latent variable techniques to examine the pattern of relations among the different constructs. In order to derive latent variables for the constructs of interest, multiple indicators of each cognitive construct were used. This was done in order to ensure that any lack of a relation found would not be due to unreliability or idiosyncratic task effects. Therefore, multiple measures of each cognitive construct were used to create latent variables. By examining a large number of participants and a large and diverse number of measures we should be able to better characterize the nature of individual differences in WM and its relation with gF.

2. Method

2.1. Participants

A total of 171 participants (63% female) were recruited from the subject-pool at the University of Oregon and from the local Eugene, OR community. Participants were between the ages of 18 and 35 ($M = 21.4$, $SD = 3.5$) and received $10 per hour for their participation.

2.2. Materials and procedure

After signing informed consent, all participants completed color capacity, operation span, antisaccade, Raven, delayed free recall, shape capacity, symmetry span, and number series in Session 1. In Session 2, all participants completed space capacity, reading span, disengagement, Cattel's Culture Fair Test, paired associates, orientation capacity, picture source recognition, and motion capacity. In Session 3, participants completed the 48 drop task and the change detection task. All tasks were administered in the order listed above.

3. Measures

3.1. Working memory span

Ospan. Participants solved a series of arithmetic problems while trying to remember a set of unrelated letters (F, H, J, K, L, N, P, Q, R, S, T, Y). Before beginning the real trials, participants performed three practice sections. The first practice was simple letter span. A letter appeared on the screen and participants were required to recall the letters in the same order as they were presented. In all experimental conditions, letters remained on-screen for 1000 ms. At recall, participants saw a 4×3 matrix of letters. Recall consisted of clicking the box next to the appropriate letters (no verbal response was required) in correct order. The recall phase was untimed such that participants had as much time as needed to recall the letters. After recall, the computer provided feedback about the number of letters correctly recalled in current set. Next, participants performed the math portion of the task alone. Participants first saw an arithmetic problem, consisting of a sequence of operations (e.g. $(1 * 2) + 1 = ?$). Participants were instructed to solve the problem as quickly as possible and then click the mouse to advance to the next screen. On the next screen a digit (e.g., "3") was presented and the participant was required to click either a "True" or "False" box depending on their answer. After each problem participants were given accuracy feedback. The math practice served to familiarize participants with the math portion of the task as well as to calculate how long it would take that person to solve the math operations. Thus, the math practice attempted to account for individual differences in the time required to solve math operations without an additional storage requirement. After the math alone section, the program calculated each individual's mean time required to solve the equations. This time (plus 2.5 standard deviations) was then used as a time limit for the math portion of the main session for that individual. Participants completed 15 math problems in this session. The final practice session had participants perform both the letter recall and math portions together, just as they would do in the real block of trials. Here participants first saw the math problem and after they clicked the mouse button indicating that they had solved it, they saw the letter to be recalled. If a participant took more time to solve the problem than their average time plus 2.5 *SD*, the program automatically moved on and counted that trial as an error. Participants completed three practice trials each of set-size two. After participants completed all of the practice sessions, the program progressed to the real trials. The real trials consisted of three trials of each set-size, with the set-sizes ranging from 3–7. This made for a total of 75 letters and 75 math problems. Note that the order of set-sizes was random for each participant. The storage score was the number of correct items recalled in the correct position. The processing score was the mean of the median time to correctly complete the processing component of the task (processing time). See Unsworth et al. (2005) and Unsworth, Redick, et al. (2009) for more task details.

Symspan. In this task participants were required to recall sequences of red squares within a matrix while performing a symmetry-judgment task. In the storage alone practice session, participants saw sequences of red squares appearing in the matrix and at recall were required to click the correct locations in the matrix in the correct order. In the symmetry-judgment task alone session participants were shown an 8×8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical approximately half of the time. Participants performed 15 trials of the symmetry-judgment task alone. The same timing parameters used in the Ospan were used. The final practice session combined the matrix recall with the symmetry-judgment task. Here participants decided whether the current matrix was symmetrical and then were immediately presented with a 4×4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations in the preceding displays, in the order they appeared by clicking on the cells of an empty matrix. There were three trials of each set-size with list length ranging from 2 to 5. The same scoring procedure as Ospan was used. See Unsworth et al. (2005) and Unsworth, Redick et al. (2009) for more task details.

Rspan. Participants were required to read sentences while trying to remember the same set of unrelated letters as Ospan. As with the Ospan, participants completed three practice sessions. The letter practice was identical to the Ospan task. In the processing-alone session, participants were required to read a sentence and determine whether the sentence made sense (e.g. "The prosecutor's dish was lost because it was not based on fact. ?"). Participants were given 15 sentences, roughly half of which made sense. As with the Ospan, the time to read the sentence and determine whether it made sense was recorded and used as an overall time limit on the real trials. The final practice session combined the letter span task with the sentence task just like the real trials. In the real trials, participants were required to read the sentence and to indicate whether it made sense or not. Half of the sentences made sense while the other half did not. Nonsense sentences were made by simply changing one word (e.g. "dish" from "case") from an otherwise normal sentence. There were 10–15 words in each sentence. After participants gave their response they were presented with a letter for 1000 ms. At recall, letters from the current set were recalled in the correct order by clicking on the appropriate letters. There were three trials of each set-size with list length ranging from 3 to 7. The same scoring procedure as Ospan was used. See Unsworth et al. (2005) and Unsworth, Redick et al. (2009) for more task details.

3.2. Capacity

Color task. Six color circles were simultaneously presented on the computer screen for 100 ms. The colors were randomly selected from 180 isoluminant colors that were evenly distributed along a circle in the CIE Lab color space ($L = 70$, $a = 20$, $b = 38$, and radius = 60). This specific color circle was selected to maximize the discriminability of the colors (Zhang & Luck, 2008). Participants remembered as many of them as possible over a 900 ms retention interval. After the retention interval, a grey probe was presented at one of the stimulus locations along with a color ring consisted of the 180 colors. Similarly to the shape task, participants reported the color of the stimulus presented at the probe location by clicking the corresponding color on the color ring (see Fig. 1). The probe and the color ring stayed on the screen until a response was made. Participants completed 180 trials in total.

Orientation task. Six clock face stimuli consisting of a ring and a radius-long clock hand were simultaneously presented on the computer screen for 100 ms. The orientation of each clock hand was randomly selected from 1° to 360°. Participants remembered as many orientations of the clock hands as possible over a 900 ms retention interval. After the retention interval, a probe ring was presented at one of the stimulus locations. Participants reported the orientation of the clock hand presented at the probe location by clicking on the rim of the ring (see Fig. 1). The probe stayed on the screen until a response was made. Participants completed 192 trials in total.

Motion task. Six motion stimuli were simultaneously presented on the computer screen for 1 s. A motion stimulus was a circular field of moving dots whose motion were 100% coherent (i.e. all the dots moved in one direction). The motion direction for each field was randomly selected from 1° to 360°. Participants remembered as many motion directions as possible over a 900 ms retention interval. After the retention interval, a probe ring was presented at one of the stimulus locations. Similarly to the orientation task, participants reported the motion direction of the stimulus presented at the probe location by clicking on the rim of the ring (see Fig. 1). The probe stayed on the screen until a response was made. Participants completed 180 trials in total.

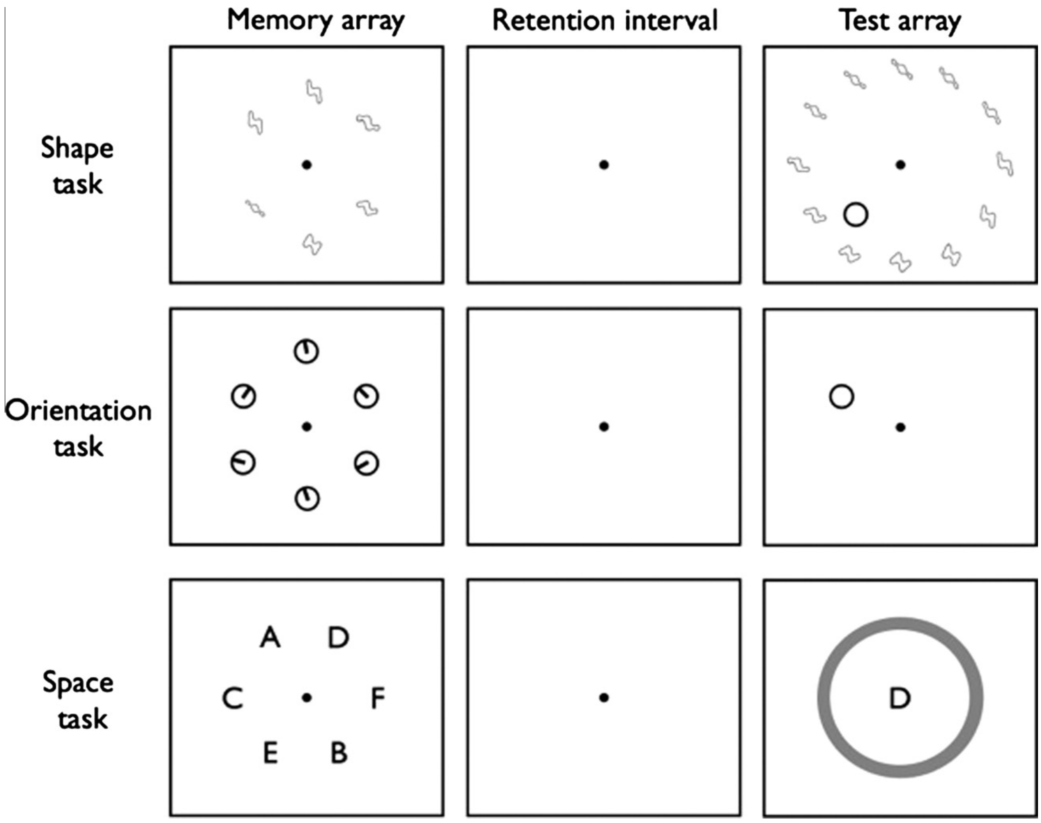

Fig. 1. The top row shows the schematic of the shape WM recall task. The memory array consisted of six shapes randomly selected from a pool of 180 shapes that vary on a circular continuum (see Zhang & Luck, 2008 for detail). When the test array was presented, participants indicated the shape at the probed location by clicking on the shape circle. They were instructed to extrapolate and click in between the shapes displayed to be as precise as possible. The middle row shows the schematic of the orientation task. The memory array presented 6 clock face stimuli. When the test array was displayed, participants indicated the orientation of the probed clock hand by clicking on the rim of the probe. They were instructed to be as precise as possible. The bottom row shows the schematic of the space task. The memory array presented six letters (A–F). When the test array was displayed, participants indicated the precise location of the probe letter (in this case "D") by clicking on the grey circle.

Shape task. Six shape stimuli were simultaneously presented on the computer screen for 1 s. Shape stimuli were randomly chosen from a stimulus set borrowed from Zhang and Luck (2008). This stimulus set consisted of 180 shapes that varies on a circular continuum. Participants remembered as many shape stimuli as possible over a 900 ms retention interval. After the retention interval, a question mark was presented at one of the stimulus locations along with a shape ring that consisted of 12 shapes that were evenly spaced on the circular shape continuum. Participants reported the shape of the stimulus presented at the probe location by clicking the corresponding location on the shape ring (see Fig. 1). Note that participants' response was not limited to the locations of 12 shapes, but they were encouraged to click in between the shapes by extrapolation. Participants completed 180 trials in total.

Space task. Six letter stimuli (A, B, C, D, E, and F) were simultaneously presented on an imaginary circle on the computer screen for 100 ms. Participants remembered as many locations of the stimuli as possible over a 900 ms retention interval. After the retention interval, a probe letter (A, B, C, D, E, or F) was presented at the center of the screen along with a grey ring at the location of the imaginary circle. Participants reported the location of the probe letter by clicking on the grey ring (see Fig. 1). The probe and the ring stayed on the screen until a response was made. Participants completed 180 trials in total.

Change detection task. At the beginning of each trial, a central arrow cue was presented for 200 ms to indicate which side (left or right) of the screen to pay attention to. Left and right side were equally likely to be cued. 500 ms afterwords, either 2 or 6 stimuli were presented on each side of the screen for 150 ms, and participants remembered the stimuli presented on the cued side while ignoring the items on the other side. After a 900 ms retention interval, one stimulus was presented on each side, and participants indicated if the stimulus on the cued side is identical to the original stimulus presented at that location. It was the same for a half of the trials. The stimuli were colored squares for a half of the trials, and geometric shapes (rectangular or oval frames with 2 lines inside, borrowed from Fukuda, Vogel, et al., 2010) for the other half. All the conditions were randomly intermixed, and participants performed 800 trials in total. Performance for set size 6 condition for each stimulus type was separately converted to a standard capacity estimate (K) by Cowan's formula (2001) as a dependent measure (shape K and color K). Specifically, $K = N * (H - FA)$, where N is the relevant set size, H is the hit rate and FA is the false alarm rate (Cowan, 2001).

3.3. Attention control

48 Drop task. Participants were presented with either 4 or 8 colored squares (set size 4 and set size 8 conditions) on the computer screen for 150 ms. Participants remembered as many colors as possible over a 900 ms retention interval. After the retention interval, one test colored square was presented at one of the original stimulus locations, and participants indicated if it was the same color as the original stimulus presented at that location. The test square had the same color in a half of the trials, and it was different for the other half of the trials. Participants completed 80 trials for each condition. Based on the performance, the number of the items held in WM (K estimate) was calculated for each set size using a standard formula (Cowan, 2001). Prior research has shown that when participants' capacities are overloaded, attention control is needed to regulate attention to prevent being captured by the overloading information (e.g., Cusak, Lehmann, Veldsman, & Mitchell, 2009). The dependent measure (48 drop) was the difference between the K estimates for set size 4 and set size 8 (i.e. K for set size $4 - K$ for set size 8).

Antisaccade. Participants stared at a fixation point that was onscreen for a variable amount of time (200–2200 ms). A white "=" sign was then flashed either to the left or right of fixation (at11.33° of visual angle) for 100 ms. This was followed by a 50-ms blank screen and a second appearance of the cue for 100 ms, making it appear as though the cue ("=") repeatedly flashed onscreen. Following another 50-ms blank screen, the target stimulus (a B, P, or R) appeared on screen for 100 ms, followed by masking stimuli (an H for 50 ms and an "8" that remained onscreen until a response was given). The participants' task was to identify the target letter by pressing a key for B, P, or R (the keys 1, 2, or 3) as quickly and accurately as possible (based on the original study by Kane, Bleckley, Conway, & Engle, 2001). Participants received, in order, 10 practice trials to learn the response mapping, 15 practice trials 40 test trials. Proportion correct was the dependent measure.

Disengagement task. The Disengagement task consisted of two parts. In the first part, the threshold target exposure duration was individually obtained. In this phase, participants were presented with four place holders for 500 ms. Then, a red square frame with a gap on one side was presented as a target in one of the place holders along with three more differently colored square frames (blue, green, or magenta) filling in the other place holders. After a target exposure duration (initially set to 500 ms), color patch masks were presented over all the place holders. Participants' task was to report the direction of the gap on the target. The exposure duration was titrated every trial to establish a threshold target exposure duration with which each individual can perform the task with about 75% accuracy (Fukuda & Vogel, 2011). Participants completed 4 blocks of 60 trials, and the average exposure duration for the last 20 trials in the last 3 blocks was used as the threshold target exposure duration.

In the second part, attentional disengagement was assessed. In this phase, participants performed essentially the same task with the fixed target exposure time defined for each individual. The difference however, was that on 1/3 of the trials, a colored square frame (distractor) was briefly presented on a periphery of a place holder prior to the target onset. A half of the distractors were red (contingent), and the other half were either green, blue or magenta. Participants completed 720 trials in total. The dependent measure was the difference in the accuracy for no distractor condition and contingent distractor condition (distractor to target SOA = 150 ms).

3.4. Secondary memory

Picture source recognition. During the encoding phase, participants were presented with a picture (30 total pictures) in one of four different quadrants onscreen for 1 s. Participants were explicitly instructed to pay attention to both the picture (item) as well as the quadrant it was located in (source).

At test participants were presented with 30 old and 30 new pictures in the center of the screen. Participants were required to indicate if the picture was new or if it was old, what quadrant it was presented in via key press. Thus, on each test trial participants pressed one of five keys indicating new, top left, top right, bottom left, or bottom right. Participants had 5 s to press the appropriate key to enter their response. A participant's score was the proportion of correct responses.

Paired associates. Participants were given 3 lists of 10 word pairs each. All words were common nouns and the word pairs were presented vertically for 2 s each. All word pairs were associatively and semantically unrelated. Participants were told that the cue would always be the word on top and the target would be on bottom. After the presentation of the last word participants saw the cue word and ??? in place of the target word. Participants were instructed to type in the target word from the current list that matched cue. Cues were randomly mixed so that the corresponding target words were not recalled in the same order as they were presented. Participants had 5 s to type in the corresponding word. A participant's score was proportion of items recalled correctly.

Delayed free recall. Participants recalled 6 lists of 10 words each. All words were common nouns that were presented for 1 s each. After list presentation, participants engaged in a 16 s distractor task before recall: Participants saw 8 three-digit numbers appear for 2 s each, and were required to write the digits in ascending order. After the distractor task participants typed as many words as they could remember from the current list in any order they wished. Participants had 45 s for recall. A participant's score was the total number of items recalled correctly.

3.5. gF

Raven advanced progressive matrices. The Raven is a measure of abstract reasoning. The test consists of 36 items presented in ascending order of difficulty. Each item consists of a display of 3 $\times$ 3 matrices of geometric patterns with the bottom right pattern missing. The task for the participant is to select among eight alternatives, the one that correctly completes the overall series of patterns. Participants had 10 min to complete the 18 odd-numbered items. A participant's score was the total number of correct solutions.

Number series. In this task participants saw a series of numbers and were required to determine what the next number in the series should be. That is, the series followed some unstated rule which participants were required to figure out in order to determine which the next number in the series should be. Participants selected their answer out of five possible numbers that were presented. Participants had 4.5 min to complete 15 test items. A participant's score was the total number of items solved correctly.

Cattell's culture fair test. This task is composed of four separate and timed paper-and-pencil subtests (Cattell, 1971). Particiapants were allowed 2.5–4 min to complete each subtest. In the first subtest (Series) participants saw 13 incomplete, progressive series of abstract shapes and figures, along with 6 alternatives for each, and selected the alternative that best completed the series. In the second subtest (Classifications) participants saw 14 problems composed of abstract shapes and figures, and selected the two out of the five that differed from the other three. Figures and shapes differed in size, orientation, or content. The third subtest was (Matrices) participants were presented with 13 incomplete matrices containing four to nine boxes that had abstract figures and shapes as well as an empty box and six choices. Participants had to infer the relationships among the items in the matrix and choose an answer that correctly completed each matrix. In the final subtest (Conditions) participants saw 10 sets of abstract figures consisting of lines and a single dot along with five alternatives. The participants had to assess the relationship among the dot, figures, and lines, and choose the alternative in which a dot could be placed according to the same relationship. A participant's score was the total number of items solved correctly across all four subtests.

4. Results

Descriptive statistics are shown in Table 1. Most measures had generally acceptable values of reliability and most of the measures were approximately normally distributed with values of skewness

Table 1
Descriptive statistics and reliability estimates for all measures.

Measure	M	SD	Skew	Kurtosis	Reliability
OspanS	58.43	13.89	−1.61	3.28	.80
SymspanS	30.15	8.06	−.83	.48	.78
RspanS	55.51	14.14	−1.11	1.30	.83
Color	2.43	.92	.23	.23	.70
Shape	1.95	1.47	.09	−1.20	.46
Space	4.76	.85	−1.44	2.50	.81
Orient	1.91	1.01	−.09	−.55	.76
Motion	1.73	1.06	.08	−.54	.74
ColorK	1.91	.77	.02	.18	.77
ShapeK	1.58	.95	.30	−.34	.81
Disengage	.09	.07	.23	.20	.22
Anti	.63	.14	.10	−.27	.71
48Drop	.32	1.01	−.21	−.05	.22
Picsour	.76	.15	−1.11	1.77	.80
PA	.50	.25	.08	−1.03	.85
DFR	.57	.14	.36	−.15	.73
Raven	10.42	2.99	−.11	.03	.74
NS	9.63	2.63	.05	−.68	.70
CF	34.14	4.81	−.29	1.54	.70
OspanP	3150	853	.99	1.01	.98
SymspanP	1954	603	1.82	4.80	.97
RspanP	3650	813	.61	.46	.98

Note. OspanS = operation span storage; SymspanS = symmetry span storage; RspanS = reading span storage; Color = color capacity task; Shape = shape capacity task; Space = space capacity task; Orient = orientation capacity task; Motion = motion capacity task; ColorK = K estimate from color change deterction task; ShapeK = K estimate from shape change detection task; Disengage = disengagement task; Anti = antisaccde; 48Drop = 48 drop change detection task; Picsour = picture source recognition task; PA = paired associates task; DFR = delayed free recall; Raven = Raven Advanced Progressive Matrices; NS = Number Series; CF = Cattell's Culture Fair Test; OspanP = operation span processing time; SymspanP = symmetry span processing time; RspanP = reading span processing time.

and kurtosis under the generally accepted values.[1] Correlations among the laboratory tasks, shown in Table 2, were weak to moderate in magnitude with measures of the same construct generally correlating stronger with one another than with measures of other constructs, indicating both convergent and discriminant validity within the data.

4.1. Working memory storage

First, confirmatory factor analysis was used to test several measurement models to determine the structure of the data. Specifically, five measurement models were specified to determine how WM storage, capacity, AC, SM, and gF were related to one another. Measurement Model 1 tested the notion that WM storage, capacity, AC, and SM are best conceptualized as a single unitary construct. This could be due to a single executive attention factor that is needed in all (e.g., Engle, Tuholski, Laughlin, & Conway, 1999). Thus, in this model all of the memory and attention measures loaded onto a single factor and the three gF measures loaded onto a separate gF factor and these factors were allowed to correlate. Measurement Model 2 tested the notion that WM storage and AC were best thought of as a single factor, but this factor was separate from the capacity and SM factors and all were allowed to correlate with the gF factor. This could be due to the fact that WM storage measures primarily reflect attention control abilities which are distinct from more basic memory abilities. Thus, in this

[1] Both the Disengage and 48 drop measures had less than desirable reliability estimates. This is likely due to the fact that these measures are difference scores which tend to be somewhat unreliable. Despite this, these two measures significantly correlated with many other measures and significantly loaded on the attention control factor. Furthermore, it is well known that confirmatory factor analysis and structural equation modeling partially correct for measurement error in the indicators and thus, path coefficients and latent correlations are disattenuated and the standard errors are adjusted accordingly (e.g., DeShon, 1998). Thus, despite their low reliability estimates for these measures, the overall constructs still provide a reasonable assessment of the attention control construct.

Table 2
Correlations among all measures.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1. OspanS	–																					
2. SymspanS	0.56	–																				
3. RspanS	0.72	0.52	–																			
4. Color	0.30	0.23	0.34	–																		
5. Shape	0.25	0.29	0.25	0.46	–																	
6. Space	0.23	0.28	0.35	0.49	0.33	–																
7. Orient	0.19	0.30	0.26	0.46	0.45	0.40	–															
8. Motion	0.15	0.28	0.20	0.36	0.50	0.35	0.69	–														
9. ColorK	0.07	0.15	0.22	0.36	0.27	0.23	0.38	0.35	–													
10. Shapek	0.15	0.35	0.21	0.32	0.39	0.21	0.42	0.37	0.62	–												
11. Disengage	−0.12	−0.16	−0.11	−0.16	−0.32	−0.30	−0.34	−0.34	−0.17	−0.15	–											
12. Anti	0.36	0.34	0.30	0.27	0.29	0.28	0.32	0.30	0.15	0.29	−0.29	–										
13. 48Drop	−0.11	−0.13	−0.11	−0.35	−0.35	−0.11	−0.26	−0.29	−0.34	−0.37	0.29	−0.19	–									
14. Picsour	0.20	0.24	0.25	0.28	0.27	0.22	0.39	0.38	0.21	0.24	−0.11	0.38	−0.16	–								
15. PA	0.33	0.18	0.41	0.23	0.21	0.16	0.21	0.25	0.13	0.16	−0.02	0.28	−0.07	0.43	–							
16. DFR	0.29	0.18	0.41	0.26	0.25	0.23	0.27	0.23	0.15	0.12	−0.18	0.35	−0.06	0.30	0.53	–						
17. Raven	0.22	0.33	0.34	0.33	0.28	0.23	0.33	0.37	0.28	0.32	−0.15	0.30	−0.20	0.37	0.34	0.35	–					
18. NS	0.17	0.27	0.22	0.23	0.28	0.22	0.41	0.40	0.07	0.23	−0.21	0.40	−0.06	0.30	0.16	0.26	0.37	–				
19. CF	0.31	0.35	0.38	0.30	0.27	0.17	0.38	0.39	0.22	0.29	−0.16	0.43	−0.17	0.45	0.43	0.36	0.46	0.41	–			
20. OspanP	−0.16	−0.18	−0.16	−0.26	−0.16	−0.27	−0.18	−0.15	−0.10	−0.11	0.21	−0.30	0.15	0.01	−0.02	−0.15	−0.19	−0.40	−0.24	–		
21. SymspanP	−0.11	−0.21	−0.12	−0.25	−0.15	−0.12	−0.07	−0.10	−0.06	−0.14	0.06	−0.17	0.17	−0.10	−0.21	−0.10	−0.24	−0.18	−0.33	0.4	–	
22. RspanP	−0.09	−0.01	−0.27	−0.32	−0.09	−0.34	−0.13	−0.12	−0.18	−0.07	0.06	−0.20	0.02	−0.06	−0.20	−0.25	−0.18	−0.17	−0.29	0.46	0.22	–

Note. OspanS = operation span storage; SymspanS = symmetry span storage; RspanS = reading span storage; Color = color capacity task; Shape = shape capacity task; Space = space capacity task; Orient = orientation capacity task; Motion = motion capacity task; ColorK = K estimate from color change detection task; ShapeK = K estimate from shape change detection task; Disengage = disengagement task; Anti = antisaccde; 48Drop = 48 drop change detection task; Picsour = picture source recognition task; PA = paired associates task; DFR = delayed free recall; Raven = Raven Advanced Progressive Matrices; NS = Number Series; CF = Cattell's Culture Fair Test; OspanP = operation span processing time; SymspanP = symmetry span processing time; RspanP = reading span processing time. Correlations > .14 are significant at $p < .05$ level.

Table 3
Fit indices for all models.

Model	χ^2	*df*	RMSEA	NNFI	CFI	AIC
WM storage						
Measurement Model 1	496.72	150	.12	.87	.89	576.72
Measurement Model 2	324.33	145	.09	.93	.94	414.33
Measurement Model 3	338.31	145	.09	.92	.93	428.31
Measurement Model 4	434.71	145	.11	.89	.90	524.71
Measurement Model 5	250.31	141	.07	.95	.96	348.31
SEM Mediation	297.59	144	.08	.93	.94	389.59
Mediation Fix WM-AC	315.57	145	.08	.92	.93	405.57
Mediation Fix WM-Cap	304.17	145	.08	.92	.93	394.17
Mediation Fix WM-SM	326.70	145	.09	.91	.92	416.70
Mediation Fix WM-gF	297.63	145	.08	.93	.94	387.63
Mediation Fix AC-gF	306.02	145	.08	.93	.94	396.02
Mediation Fix Cap-gF	319.19	145	.08	.93	.94	409.19
Mediation Fix SM-gF	309.95	145	.08	.93	.94	399.95
WM processing and storage						
Measurement Model	374.23	193	.07	.93	.94	494.23
Processing & Storage SEM	62.40	24	.09	.90	.93	104.40
SEM Mediation	418.60	198	.08	.92	.93	528.60

Note. RMSEA = root mean square error of approximation; NNFI = non-normed fit index; CFI = comparative fit index; AIC = Akaike information criterion.

model the WM storage and AC measures loaded onto a single factor, the capacity measures loaded onto a separate capacity factor, the SM measures loaded onto a separate SM factor and all of these factors were allowed to correlate with each other and with the gF factor. Measurement Model 3 tested the notion that WM storage and SM were best thought of as a single factor that was separate from AC and capacity. This would suggest that WM storage measures primarily reflect secondary memory abilities which are distinct from attention control abilities and differences in capacity (e.g., Ericsson & Kintsch, 1995; Mogle et al., 2008). Thus, the WM storage measures and all of the SM measures loaded onto a single factor, while the AC measures loaded on another factor and the capacity measures loaded onto a separate factor. All of the factors were allowed to correlate with one another and with gF. Measurement Model 4 tested the notion that WM storage and capacity were best thought of as a single factor, but this factor was separate from the AC and SM factors and all were allowed to correlate with the gF factor. This could be due to the fact that WM storage measures primarily reflect differences in the capacity or scope of attention (e.g., Cowan et al., 2005). Thus, in this model the WM storage and the capacity measures loaded onto a single factor, the AC measures loaded onto a separate AC factor, the SM measures loaded onto a separate SM factor and all of these factors were allowed to correlate with each other and with the gF factor. Finally, Measurement Model 5 suggested that WM storage, AC, capacity, and SM were best thought of as distinct factors that are related to one another and to gF. Thus, in this model all of the WM storage measures loaded onto a WM storage factor, all of the AC measures loaded onto an AC factor, all of the capacity measures loaded onto a capacity factor, and all of the SM measures loaded onto a SM factor. The factors were allowed to correlate with each other and with gF. Note, to improve model fit in all models we allowed the error variances for the Color and Shape K measures to correlate.[2]

[2] Model fits were assessed via the combination of several fit statistics. These include chi-square, root mean square error of approximation, standardized root mean square residual, the non-normed fit index, and the comparative fit index. The chi-square statistic reflects whether there is a significant difference between the observed and reproduced covariance matrices. Therefore, nonsignificant values are desirable. However, with large sample sizes even slight deviations can result in a significant value. Also reported is the root mean square error of approximation (RMSEA) which reflects the average squared deviation between the observed and reproduced covariances. In addition, the non-normed fit index (NNFI) and the comparative fit index (CFI) which compare the fit of the specified model to a baseline null model are reported. NNFI, and CFI values greater than .90 and RMSEA values less than .10 are indicative of acceptable fit (Kline, 1998). Finally, the Akaike information criterion (AIC) examines the relative fit between models in which the model with the smallest AIC is preferred.

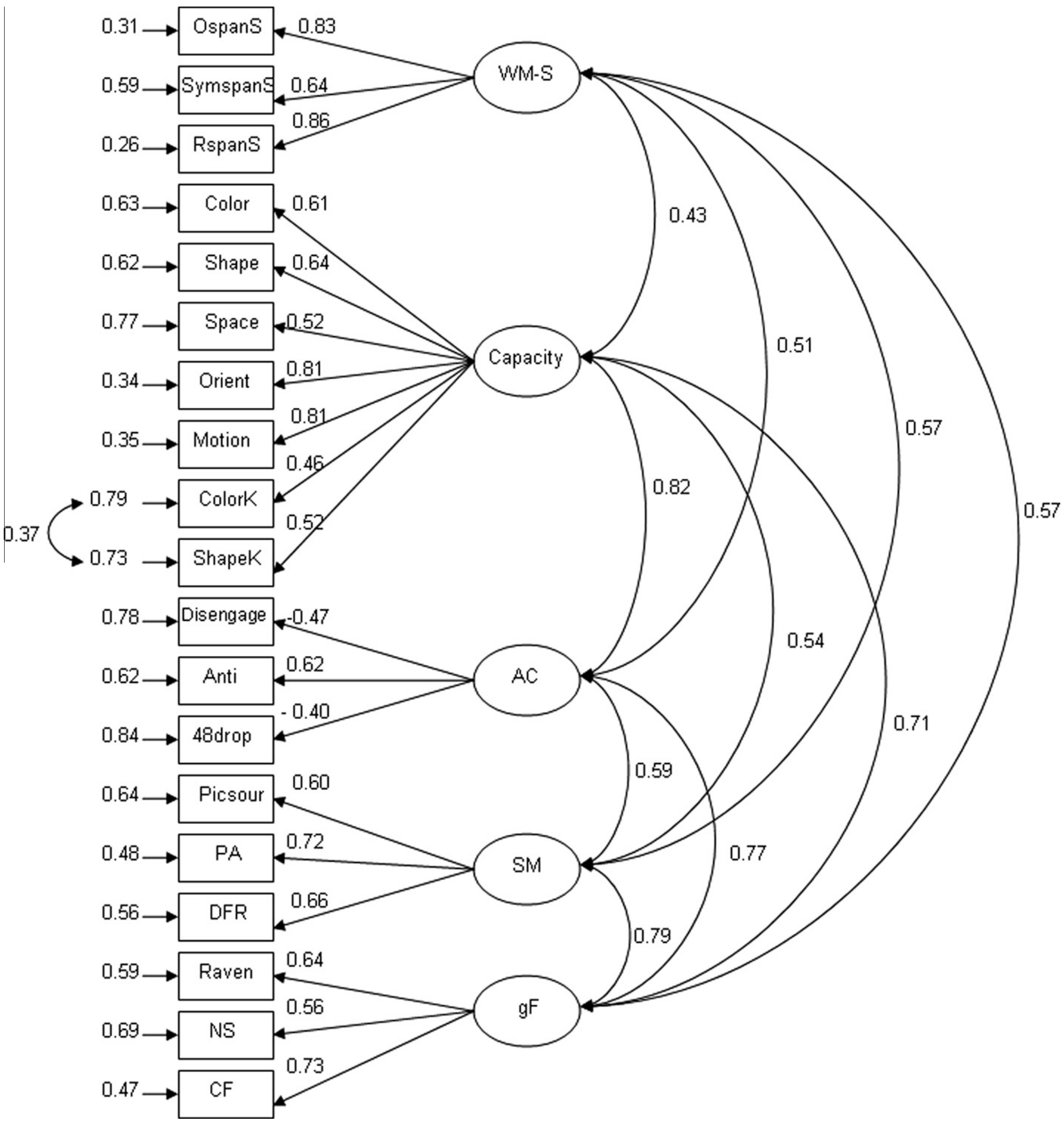

Fig. 2. Model for working memory storage (WM-S), Capacity, attention control (AC), secondary memory (SM), and fluid intelligence (gF). Paths connecting latent variables (circles) to each other represent the correlations between the constructs, the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task. All loadings and paths are significant at the $p < .05$ level.

Shown in Table 3 is the fit of the different measurement models. As can be seen, Measurement Model 5 that specified separate, yet correlated, factors provided the best fit. Specifically, Measurement Model 5 fit significantly better than the other four models (all $\Delta\chi^2$'s > 74, p's < .01), and had the lowest AIC value. Shown in Fig. 2 is the resulting model. As can be seen all tasks loaded significantly on their construct of interest and all of the latent variables were moderately related to one another. Specifically, consistent with prior research WM storage was moderately to strongly related with attention control, capacity, secondary memory, and gF (Cowan et al., 2005; Unsworth & Spillers, 2010a). Additionally, attention control was significantly related with secondary memory and gF (Unsworth & Spillers, 2010a). Interestingly, attention control and capacity were strongly related suggesting that the number of distinct representations that can be maintained is strongly related to the ability to control attention and filter out irrelevant information and prevent attentional capture (Fukuda & Vogel, 2011; Vogel, McCollough, & Machizawa, 2005). Finally, capacity and secondary memory were

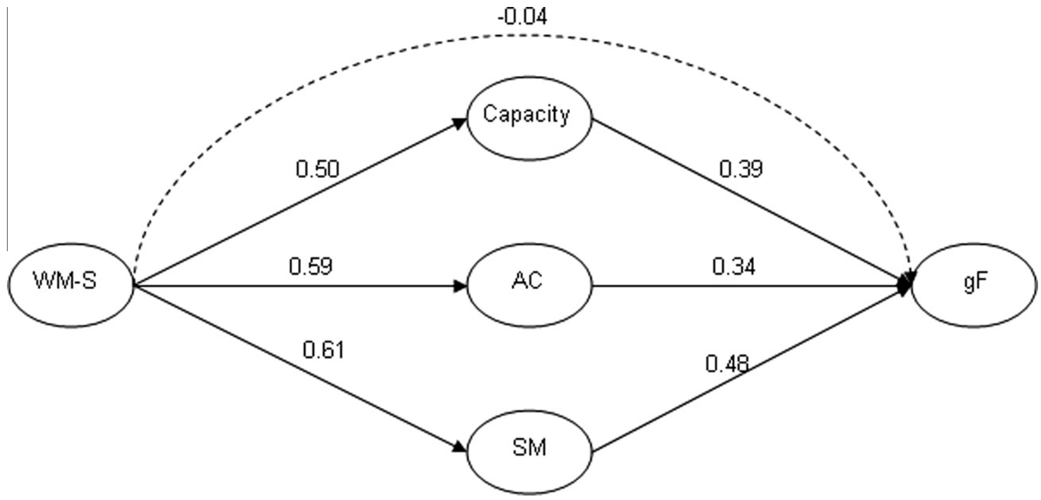

Fig. 3. Structural equation model for working memory storage (WM-S), capacity, attention control (AC), secondary memory (SM), and fluid intelligence (gF). Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients indicating the unique contribution of the latent variable. Solid lines are significant at the $p < .05$ level and dotted lines are not significant at the $p < .05$ level.

correlated. Collectively these results suggest that these different factors are all related to one another and to gF. Importantly, none of the latent correlations were equal to 1.0 suggesting that these factors are not entirely redundant constructs.

In order to test one of our primary questions of interest we next specified a model in which WM storage predicted capacity, attention control, secondary memory, and gF. Capacity, attention control, and secondary memory, also predicted gF. This model tests whether capacity, attention control, and secondary memory mediate the relation between WM storage and gF. If these factors do mediate the relation we should see that WM storage predicts all three factors, all three factorss significantly predict gF, but WM storage no longer has a direct effect on gF. This would suggest that the factors fully mediate the relation. If, however, WM storage still predicts gF after controlling for these other factors, then some other factor is also needed to explain the relation. As shown in Table 3 the fit of this model was good. Shown in Fig. 3 is the resulting model. As can be seen, WM storage significantly predicted each of the factors suggesting that WM storage is uniquely related to each of the factors (capacity, attention control, and secondary memory retrieval). Additionally, each of the factors significantly predicted gF suggesting that each of the factors contributes to variation in gF. Most importantly, the direct path from WM storage to gF was not significant. That is, the correlation between WM storage and gF went from $r = .57$ to roughly zero after statistically controlling for the other factors. Thus, capacity, attention control, and secondary memory jointly mediated the relation between WM storage and gF. Once these three factors were taken into account WM span no longer predicted residual variance in gF. Furthermore, as shown in Table 3, fixing any of the paths from WM storage to the three factors (AC, SM, capacity) to zero resulted in significantly worse model fits (all $\Delta\chi^2$'s > 6.5, p's < .01). Likewise, fixing any of the paths from the three factors to gF to zero resulted in significantly worse model fits (all $\Delta\chi^2$'s > 8.4, p's < .01). However, fixing the path from the residual WM storage factor to gF to zero, did not change the model fit ($\Delta\chi^2 = .04$, $p > .84$). Thus, omitting any of the paths from WM storage to the three factors or from the factors to gF would reduce the fit of the model and limit the ability to account for variance in gF. These results are directly in line with the multifaceted view of WM which suggests that primary memory (capacity and attention control) and secondary memory underlie individual differences in WM span and account for their predictive power (Unsworth & Engle, 2007a; Unsworth & Spillers, 2010a).

4.2. Working memory processing and storage

Next, we added WM processing into the models to determine its relation with the other constructs. Specifically we specified the same measurement model shown in Fig. 2 (Measurement Model 5), and

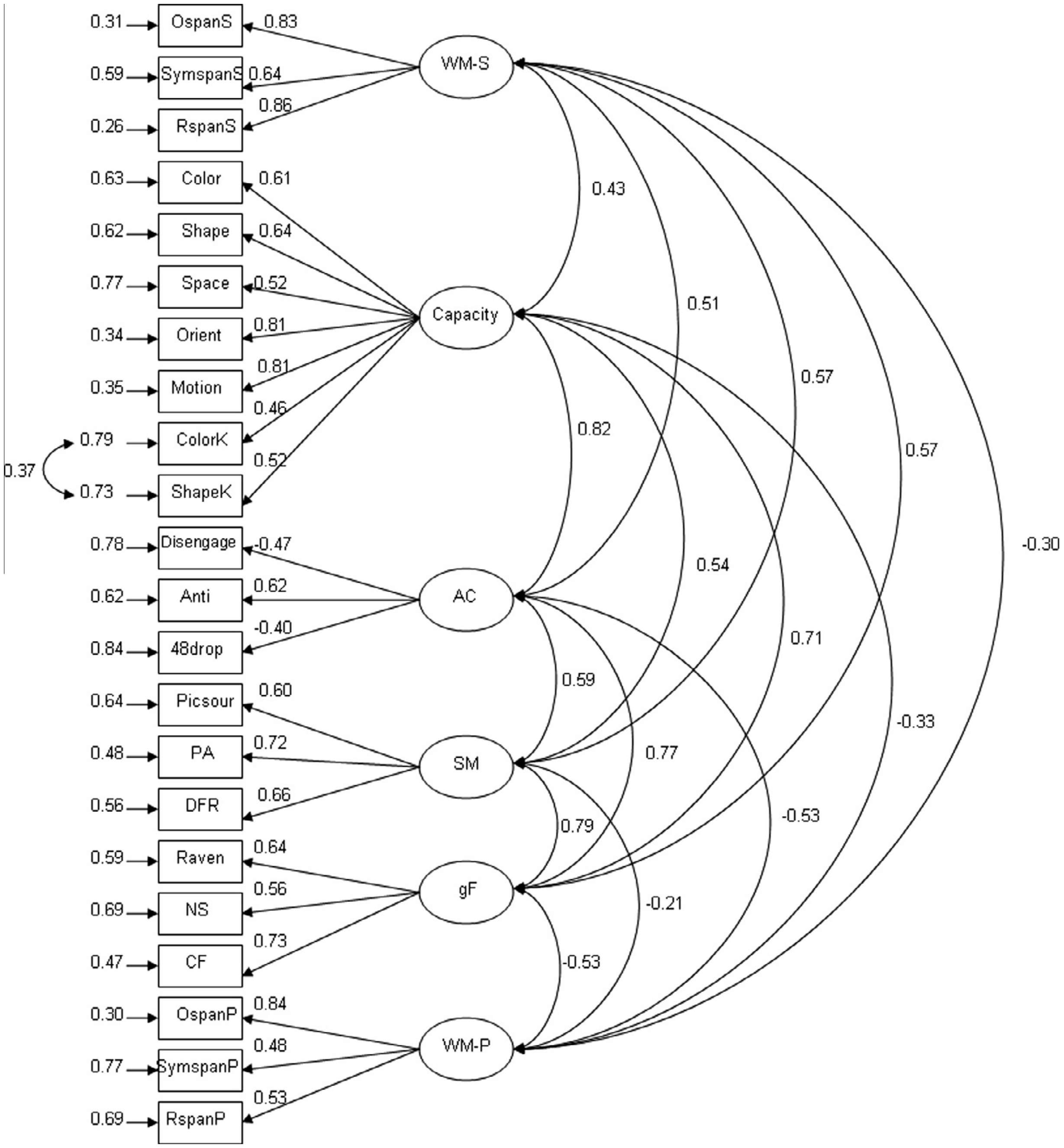

Fig. 4. Model for working memory storage (WM-S), Capacity, attention control (AC), secondary memory (SM), fluid intelligence (gF), and working memory processing (WM-P). Paths connecting latent variables (circles) to each other represent the correlations between the constructs, the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task. All loadings and paths are significant at the $p < .05$ level.

added in a factor for WM processing based on the three processing time measures taken from the complex span tasks. As shown in Table 3 the fit of this model was good. Shown in Fig. 4 is the resulting model. Consistent with prior research WM processing and WM storage were negatively correlated and WM processing was more strongly correlated with gF than with WM storage (e.g., Unsworth, Redick, et al., 2009). WM processing was also weakly and negatively correlated with capacity and SM. However, WM processing demonstrated a moderate correlation with AC suggesting that AC abilities are needed during the processing components of complex span tasks. Thus, WM processing and WM storage demonstrated differential relations with capacity, AC, and SM, with WM storage being moderately related to all, but WM processing being more related to AC than to capacity or SM.

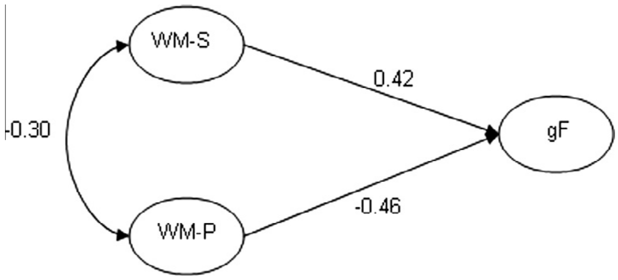

Fig. 5. Structural equation model for working memory storage (WM-S), working memory processing (WM-P), and fluid intelligence (gF). Double headed arrows connecting the latent factors represent the correlations among the factors. Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients indicating the unique contribution of the latent variable. Solid lines are significant at the $p < .05$ level.

Our next model examined whether WM processing would account for the relation between WM storage and gF or whether both would contribute independently to gF. To examine this we specified a model in which both WM storage and WM processing predicted gF and WM storage and WM processing were correlated. If WM processing accounts for the relation between WM storage and gF we should see that WM processing and WM storage are related, but only WM processing significantly predicts gF. If both contribute independently to gF we should see that both predict gF. The fit of the model was acceptable (see Table 3). As shown in Fig. 5 both WM storage and WM processing predicted gF. Collectively, 50% of the variance in gF was accounted for with WM storage uniquely accounting for 18%, WM processing uniquely accounting for 21%, and both shared 11% of the variance. Consistent with prior research these results suggests that WM storage and WM processing make independent contributions to higher-order cognition and in particular to gF (Bayliss et al., 2003; Logie & Duff, 2007; Unsworth, Redick, et al., 2009; Waters & Caplan, 1996).

For our final model we examined whether capacity, AC, and SM would mediate the relations between WM storage and WM processing with gF. That is, similar to the model shown in Fig. 3, we wanted to examine whether capacity, AC, and SM would mediate not only the relation between WM storage and gF, but also the relation between WM processing and gF. Therefore, we specified a model in which WM storage and WM processing were correlated and both predicted capacity, AC, and SM. The paths from WM storage and WM processing to gF were set to zero. Capacity, attention control, and secondary memory, were specified to predict gF. As shown in Table 3 the fit of the model was good. Shown in Fig. 6 is the resulting model. As can be seen, WM storage was significantly related to capacity, AC, and SM. Likewise, WM processing was related to capacity, AC, and SM, but the

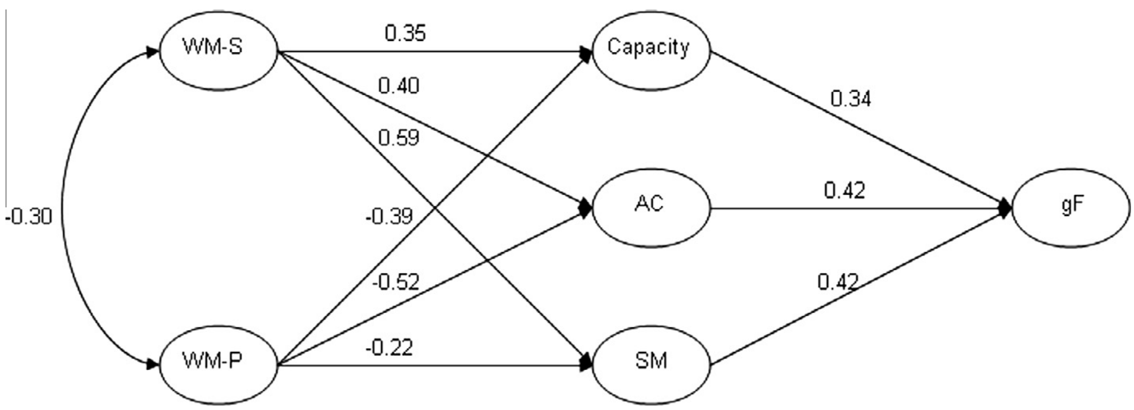

Fig. 6. Structural equation model for working memory storage (WM-S), capacity, attention control (AC), secondary memory (SM), working memory processing (WM-P), and fluid intelligence (gF). Double headed arrows connecting the latent factors represent the correlations among the factors. Single-headed arrows connecting latent variables (circles) to each other represent standardized path coefficients indicating the unique contribution of the latent variable. Solid lines are significant at the $p < .05$ level.

strongest relation was with AC. Furthermore, capacity, AC, and SM all significantly predicted gF with 81% of the variance being accounted for in gF. Importantly, freeing the paths from WM storage and WM processing to gF did not change the model fit ($\Delta\chi^2(2) = 3.98$, $p > .14$), indicating that the paths were not significant and did not uniquely predict gF. Thus, consistent with the prior model the relation between WM storage and gF was fully mediated by capacity, AC, and SM. Additionally, the relation between WM processing and gF was also mediated by the three factors with much of the relation being accounted for by AC. Overall, these results suggest that although WM storage and WM processing make independent contributions to gF, both of these contributions are accounted for by variation in capacity, AC, and SM.

4.3. Variance partitioning

To explore the shared and unique contribution of each latent factor with gF further, we utilized variance partitioning methods that have been used previously (e.g., Chuah & Maybery, 1999; Cowan et al., 2005). Variance partitioning attempts to allocate the overall R^2 of a particular criterion variable (here gF) into portions that are shared and unique to a set of predictor variables (here capacity, SM, and AC). Note, because only capacity, SM, and AC accounted for unique variance they were included in the variance portioning analyses. WM storage and WM processing did not account for unique variance, and thus were not included. A series of regression analyses was carried out to obtain R^2 values from different combinations of the predictor variables in order to partition the variance. For each variable entering into the regression, the latent correlations from the previous confirmatory factor analysis (i.e., Measurement Model 5) were used.

As shown in Fig. 7, the results suggested that a total of 78% of the variance in gF was accounted for by the three constructs. Of this variance, 38% was shared by all three of the constructs (capacity, AC, and SM), whereas the remaining 40% was accounted for by both unique and shared variance across the three constructs. Specifically, both capacity and AC accounted for a small portion of unique variance, but they accounted for 9% shared variance. Secondary memory accounted for a large portion of unique variance (17%), but also shared 7% with AC. Thus, all three factors are needed to account for variation in gF.

4.4. Cluster analysis

The final set of analyses utilized cluster analytic techniques to determine if subgroups of participants were present in the data based on differences in the three component processes. Specifically, it is possible that some participants have limitations in the number of items that can maintained (capacity), while others have limitations in terms of the ability to control attention and prevent

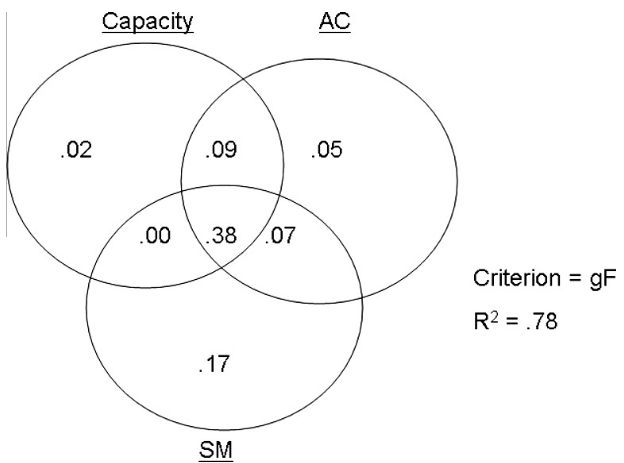

Fig. 7. Venn diagrams indicating the shared and unique variance accounted for in fluid intelligence (gF), by measures of capacity, attention control (AC), and secondary memory (SM).

distractors from gaining access to WM (attention control), and still others may have limitations in the ability to retrieve items from SM and bring them into primary memory (controlled retrieval from secondary memory). In order to examine the possibility of subgroups of participants who have specific deficits in one process, rather than global deficits manifested on all processes cluster analysis was used. Cluster analysis is a tool used to determine group membership by minimizing within group differences and maximizing between group differences (Everitt, Landau, & Leese, 2001; Kaufman & Rousseeuw, 2005). Groups are formed where individuals in the group are very similar to one another but unlike individuals in other groups. It should be noted that these methods are largely atheoretical and group membership is merely based on empirical similarities within a cluster and differences across clusters.

In order to examine possible subgroups in the three component processes, factor composites for capacity, AC, and SM were formed (see Unsworth, 2009 for a similar approach). Next, the three factor composites were entered into a two-step cluster analysis. In this analysis, cases were first grouped into pre-clusters at the first step by constructing a cluster feature tree (see Zhang, Ramakrishnan, & Livny, 1996). For each case the algorithm determined if the case should be included with a previously formed pre-cluster or a new pre-cluster should be created based on the cluster feature tree. In the second stage an agglomerative hierarchical clustering method was used on the pre-clusters and allowed for an exploration of different numbers of clusters. In this stage clusters were recursively merged until the desired number of clusters was determined by the algorithm. In these analyses, distance between clusters was based on a log-likelihood measure whereby distance was related to the decrease in log-likelihood as the clusters were formed into a single cluster. The algorithm automatically determines the number of clusters by taking into account the lowest information criterion (here AIC) and the highest ratio of distance measures (indicating the best separation of the clusters).

The cluster analysis suggested the presence of five groups consisting of 34, 30, 40, 35, and 32 participants each. Shown in Table 4 are the resulting groups' scores on each respective factor. Specifically, as shown in Table 4 looking at capacity suggested that Groups 1 and 4 were weak in capacity whereas Group 5 was strong in capacity and Groups 2 and 3 were more average in capacity. A one-way ANOVA on the capacity scores confirmed these impressions, $F(4,166) = 63.98$, $MSE = .34$, $p < .01$, partial $\eta^2 = .61$. Bonferroni post hoc comparisons suggested that there were significant differences (all $ps < .01$) between all of the groups in capacity (except for Groups 2 and 3, which did not differ [$p > .50$]).[3] As shown in Table 4, examining AC suggested that Group 1 was weak in AC, while Groups 2 and 5 were strong in AC abilities and Groups 3 and 4 were more average in AC. These impressions were confirmed with a one-way ANOVA on AC scores, $F(4,166) = 83.38$, $MSE = .19$, $p < .01$, partial $\eta^2 = .67$. Bonferroni post hoc comparisons suggested that there were significant differences (all $ps < .01$) between all of the groups in AC (except for Groups 2 and 5, which did not differ [$p > .90$] and Groups 3 and 4, which did not differ [$p > .90$]). Finally, as shown in Table 4, examining SM scores suggested that Group 1 was weak in SM, whereas Groups 4 and 5 were strong in SM and Groups 2 and 3 were average to weak in SM. A one-way ANOVA on the SM scores suggested significant differences between the groups, $F(4,166) = 71.69$, $MSE = .30$, $p < .01$, partial $\eta^2 = .64$. Bonferroni post hoc comparisons suggested that there were significant differences (all $ps < .01$) between all of the groups in SM (except for Groups 2 and 3, which did not differ [$p > .90$] and Groups 4 and 5, which did not differ [$p > .17$]). Importantly, the pattern of results across the three factors suggested that some of the groups demonstrated specific deficits or strengths on one factor rather than necessarily all factors. Other groups, however, demonstrated deficits on all factors or strengths on all factors. Specifically, Group 1 consisted of low ability participants who scored below average on all three factors and tended to have the lowest overall scores on each factor. Group 2 consisted of individuals who were above average on both capacity and AC, but were relatively weak on SM. In fact, this group had some of the strongest AC scores. Thus, this group demonstrated clear strengths on capacity and AC, but slight deficits on SM. Group 3 consisted of individuals who were close to average on all three factors. Group 4, demonstrated below average capacity and weak to average AC, but above average SM. In fact, this group demonstrated some of the strongest SM scores.

[3] Differences between the groups was also found when just examining the K estimates from the change detection task, $F(4,166) = 16.76$, $MSE = .44$, $p < .01$, partial $\eta^2 = .29$. Group 1 $K = 1.24$ ($SE = .12$), Group 2 $K = 2.06$ ($SE = .15$), Group 3 $K = 1.86$ ($SE = .10$), Group 4 $K = 1.32$ ($SE = .11$), Group 5 $K = 2.33$ ($SE = .06$).

Table 4
Descriptive statistics for each group defined by the cluster analysis on measures of capacity, attention control, secondary memory, working memory storage, working memory processing, and fluid intelligence.

Measure	Group 1	Group 2	Group 3	Group 4	Group 5
Capacity	−.98 (.09)	.49 (.12)	.21 (.08)	−.61 (.12)	.99 (.09)
AC	−.86 (.07)	.81 (.06)	−.17 (.05)	−.27 (.08)	.70 (.10)
SM	−.81 (.12)	−.44 (.10)	−.41 (.08)	.70 (.10)	1.02 (.07)
WM-S	−.58 (.22)	.12 (.14)	−.11 (.13)	.11 (.12)	.52 (.10)
WM-P	.22 (.18)	−.49 (.16)	.26 (.14)	.28 (.13)	−.43 (.09)
gF	−.60 (.14)	.11 (.18)	−.12 (.10)	−.03 (.10)	.72 (.11)

Note. Capacity = factor composite of seven capacity measures; AC = factor composite of three attention control measures; SM = composite of three secondary memory measures; WM-S = factor composite of the three working memory storage measures; WM-P = factor composite of the three working memory processing measures; gF = factor composite of the three general fluid intelligence measures. Numbers in parentheses are standard errors of the mean.

Thus, this group seems to be the exact opposite of Group 2 with these individuals demonstrating strengths in SM, but deficits in capacity and somewhat in AC. Indeed, as noted in Footnote 3 this group had some of the lowest *K* estimates. Finally, Group 5 consisted of high ability participants who scored high on all three factors and tended to have the highest overall scores on each factor.

Furthermore, as shown in Table 4, the groups tended to differ in their levels of WM storage, WM processing, and gF. Specifically, examining WM storage suggested a significant difference between the groups, $F(4,166) = 7.22$, $MSE = .75$, $p < .01$, partial $\eta^2 = .15$, with Group 1 scoring generally below the other groups and Group 5 scoring above the other groups. Bonferroni post hoc comparisons suggested that Group 1 scored significantly lower on WM storage than all other groups (all ps < .05) except for Group 3 ($p > .19$). Groups 2 and 4 only differed from Group 1 (all other p's > .52) and Group 3 only differed from Group 5 (all other p's > .19). Examining WM processing suggested a significant difference between the groups, $F(4,166) = 6.87$, $MSE = .71$, $p < .01$, partial $\eta^2 = .15$, with Groups 2 and 5 having faster WM processing times than the other groups. Specifically, Bonferroni post hoc comparisons suggested that Groups 2 and 5 differed from the other groups (all p's < .01), but did not differ from one another ($p > .90$). Furthermore, the other groups did not differ from one another (all p's > .90). Thus, both groups that scored high on AC had the fastest WM processing times. Finally, examining gF suggested a significant difference between the groups, $F(4,166) = 14.04$, $MSE = .53$, $p < .01$, partial $\eta^2 = .25$, with Group 1 scoring below the other groups and Group 5 scoring above the other groups. Specifically, Bonferroni post hoc comparisons suggested that Group 1 scored below all of the other groups (all p's < .05) and Group 5 scored above all of the other groups (all p's < .05). There were no differences between the remaining groups in gF (all p's > .90). Collectively these results suggest that individuals can have specific deficits or strengths on each of the factors leading to different profiles of performance not only on the factor measures themselves but also on measures of WM storage, WM processing, and gF.

5. Discussion

A number of theories have been put forth to explain the relation between WM and gF. Unfortunately, no single factor has been shown to fully account for the relation. In the current study we tested whether multiple factors (capacity, attention control, and secondary memory) would collectively account for the relation. Results from the latent variable analyses clearly demonstrated that variation in WM was accounted for by the three different factors as well as by task specific variance. Furthermore, it was shown that WM (both storage and processing) was uniquely related to each factor suggesting that several distinct sources of variance are present in WM. In terms of the relation between WM and gF it was found that WM correlated with gF consistent with many prior studies. Additionally, capacity, attention, control, and secondary memory were each related to gF and in the structural equation models each factor uniquely related with gF. Importantly, the three factors completely accounted for the relation between WM span and gF. That is, capacity, attention control, and secondary memory, jointly mediated the relation between WM (both storage and processing) and gF. These results are inconsistent with unitary accounts of the relation between WM and higher-order cognition suggesting that resource sharing (Case et al., 1982; Daneman & Carpenter, 1980), attention control (Engle & Kane, 2004), capacity/scope of attention (Cowan et al., 2005), or secondary memory abilities (Mogle et al., 2008), primarily account for the relation. Rather the current results are very much in line with the multifaceted view of WM, suggesting that individual differences in capacity, attention control, and secondary memory jointly account for individual differences in WM and its relation with gF.

5.1. Multifaceted nature of working memory and working memory limitations

The results of the current study point to the multifaceted nature of WM. In particular the results suggest that capacity (or scope of attention), attention control, and secondary memory are important facets of WM and are important for the predictive power of WM. In the current view WM is a system responsible for active maintenance and rapid accessibility of task-relevant information. Working memory represents a distinct set of interacting processes with each being important for a different function. This view is similar to the multi-component model which suggests that WM is comprised of distinct cognitive systems or functions (see Baddeley, 2007; Logie, 2011 for reviews). Importantly, whereas the multi-component model is primarily concerned with examining the various domain-specific components (e.g., phonological store, visual cache), the multifaceted view is primarily concerned with delimiting the important central executive type processes that are important for performance and for the relation between WM and higher-order cognition. Within the current multifaceted view we suggest that capacity, attention control, and secondary memory are three of the most important factors (although see below for other factors) that individuals differ on and account for the predictive power of WM.

In the current framework capacity refers to the ability to individuate and maintain distinct items in a highly active state. Individuals differ in the extent to which they can apprehend multiple items which results in basic differences in the number of items that can be maintained at a given time. This overall notion of capacity differences is consistent with prior work on primary memory (Craik & Levy, 1976; James, 1890; Unsworth & Engle, 2007a; Unsworth et al., 2010; Waugh & Norman, 1965) and more recent work examining the scope of attention (Cowan, 2001, 2005; Cowan et al., 2005) as well as work examining capacity limits in visual working memory (Fukuda, Awh, & Vogel, 2010; Luck & Vogel, 1997, 2013). Collectively this work suggests that a key component of WM is the ability to simultaneous apprehend multiple items in an active state in order to facilitate the processing of task relevant information (e.g., Anderson, Vogel, & Awh, 2013; Ester, Drew, Klee, Vogel, & Awh, 2012). Indeed, a recent study demonstrated that the same individual differences in capacity are observed even when the TBR items remain continuously visible to the observer, suggesting that this reflects a representational limit rather than a limit of storage (Tsubomi, Fukuda, Watanabe, & Vogel, 2013). As such, capacity will be needed in a number of situations where items need to be differentiated. For example, capacity is needed to associate multiple items so that their representations are encoded into secondary memory. Likewise capacity is needed to maintain multiple aspects of a message whether it is written text or vocal information to facilitate comprehension. In terms of fluid intelligence measures, capacity is needed to maintain distinct representations and to recombine these representations into new forms to successfully solve problems and reason about relations. Thus, within the overall WM system capacity is needed to ensure that multiple distinct items can be individuated and maintained in an active state.

Closely related to capacity is attention control. Within the current framework, attention control refers to the ability to select and actively maintain items in the presence of internal and external distraction (Engle & Kane, 2004). In particular, attention control abilities are necessary when goal-relevant information must be maintained in a highly active state in the presence of potent internal and external distraction. Any lapse of attention (or goal neglect, De Jong, Berendsen, & Cools, 1999; Duncan, 1995) will likely lead to a loss of the task goal and will result in attention being automatically captured by internal (e.g., mind-wandering; Kane et al., 2007; McVay & Kane, 2012) or external distraction (e.g., Fukuda & Vogel, 2009; Unsworth, Schrock, & Engle, 2004). Thus, attention control abilities are needed to protect items that are being held in the focus of attention (or primary memory), to effectively select target representations for active maintenance, and to filter out irrelevant distractors and prevent them from gaining access to the current focus of attention (e.g., Vogel et al., 2005). Given that attention control is needed to protect items within the capacity of the focus of attention, it is perhaps not surprising that prior work has suggested a close linkage between capacity and attention control (e.g., Cowan et al., 2006; Unsworth & Engle, 2007a; Vogel et al., 2005). The current results provide important evidence for this linkage and suggest that capacity and attention control are very much highly related. Like capacity, attention control abilities are needed in a host of activities where internal and external distraction can capture attention away from the primary task (such as reading, problem solving, or reasoning) leading to items being displaced from the current focus of attention. Within the overall WM system attention control is needed to ensure that task-relevant items are being actively maintained and attentional capture from internal and external distractors is prevented.

The final main facet within the current framework is secondary memory abilities. Secondary memory abilities refer to the ability to successfully encode information into secondary memory and to recover information that was recently displaced from the focus of attention or to bring relevant items into the focus of attention. As noted previously, given that capacity and attention control abilities are limited, it seems likely that some items will not be able to be maintained and thus, they will have to be retrieved from secondary memory. In order for information to be retrieved from secondary memory it is critically important that that information was successfully encoded in the first place and that appropriate retrieval cues can be generated to access the desired information. Thus, individuals will differ in the extent to which they can successfully encode information into secondary memory (e.g., Bailey, Dunlosky, & Kane, 2008; Unsworth & Spillers, 2010b) as well as the ability to generate cues to successfully retrieve information from secondary memory (e.g., Unsworth, Brewer, & Spillers, 2013; Unsworth, Spillers, & Brewer, 2012). These secondary memory abilities are needed in a number of situations where there is too much information to actively maintain or where potent distrators have displaced information from the current focus of attention. In such situations secondary memory abilities will be needed to recover the information to facilitate processing. Furthermore, secondary memory abilities are needed in order to bring task-relevant information into the focus of attention so that it can be combined with the current contents of the focus. Like capacity and attention control, secondary memory abilities are critical for higher-order cognitive functioning to ensure that information that could not be actively maintained can nonetheless be accessed rapidly.

The current results suggest that WM is not a unitary system, but rather is composed of multiple distinct, yet interacting, processes and that each of these processes is important for higher-order cognition. Specifically, the current results suggest that capacity, attention control, and secondary memory are all highly related yet distinct. This result is reminiscent of similar work by Miyake et al. (2000) suggesting that there separate, yet related processes of executive functioning. Furthermore, the current results suggest that these three factors mediate the relation between WM storage and WM processing measures with gF. These results clearly point to the multifaceted nature of WM and further suggest that WM limitations can arise for a number of reasons. That is, rather than assuming that WM limitations are the result of a single factor or process, the current work suggests that WM limitations can arise for a number of reasons. Specifically, individuals may have deficits in capacity that limits the number of items that they can distinctly maintain. Other individuals may have deficits in the ability to control attention such that attention is constantly captured by irrelevant distractors allowing these distractors to gain access to WM. Yet, other individuals may have specific deficits in the ability to retrieve information from secondary memory which would prevent them from successfully recovering information that had been recently displaced from the current focus of attention. The results from the cluster analysis support these notions by demonstrating that some individuals have deficits in one process, but strengths in another, while still other individuals have deficits in all processes or strengths in all (see also Unsworth, 2009). These results provide important evidence that WM limitations can be multifaceted and can potentially help resolve discrepancies in the literature where some studies find evidence for the importance of deficits in one (e.g., capacity) whereas other studies find evidence for the importance of another (e.g., attention control). These discrepancies could potentially come down to differences in the samples where one deficit is more represented than another. From a practical stand point these results suggest the importance of examining individual profiles in order to determine if deficits in an individual are across the board, or whether they are localized to a single factor. This will be important for examining known groups with WM deficits such as ADHD (e.g., Gibson, Gondoli, Flies, Dobrzenski, & Unsworth, 2010). Furthermore, given recent work examining the possibility of training WM (e.g., Redick et al., 2013), it may be important to examine whether some training regimens impact one set of processes more so than others (e.g., Gibson et al., 2013).

5.2. Processing vs. storage and other WM tasks

Consistent with prior work, the current results demonstrated that although WM processing and storage are related, they both account for unique variance in gF (Bayliss et al., 2003; Logie & Duff, 2007; Unsworth, Redick, et al., 2009; Waters & Caplan, 1996). Thus, it is not simply the case that individual differences in processing account for the relation between storage and higher-order cognition. Furthermore, the current results go beyond prior work by demonstrating that both WM processing and WM storage are related to capacity, attention control, and secondary memory and in slightly different ways. That is, whereas WM storage was related to capacity, attention control, and secondary memory to the same extent, WM processing was more strongly related to attention control than the other two factors. This suggests that during the processing phase of complex span tasks that attention control processes are critically important. This could be due to the need to use attention control to switch back and forth between the two phases or due to the need to prevent the processing phase from fully capturing attention away from the TBR items. Indeed, a recent computational model of complex span tasks suggests that during the processing phase attention control processes might be needed to remove the no longer relevant processing representations (i.e., after they have been solved) from the current focus of attention and suggest that this removal of no longer relevant representations might be one reason for the relation between complex span and other cognitive measures (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). The current results demonstrating a strong link between WM processing and attention control are certainly in line with these suggestions. Future work is needed to better examine how attention control is needed during the processing phase of the complex span tasks. For now, the results suggest that WM processing and storage are distinct and that their relations with gF are jointly accounted for by capacity, attention control, and secondary memory.

Given the strong relations between complex span tasks and other span measures (such as simple span tasks and running span tasks); it is likely that the three facets also drive the relations for these other measures as well. That is, prior research has shown that multiple factors account for variability in other memory span measures and account for the relation with gF (e.g., Unsworth & Engle, 2007b). Thus, it is likely that capacity, attention control, and secondary memory also account for individual differences in those measures, although the extent to which these factors account for variation likely differs with simple span and running span tasks likely reflecting differences in capacity more so than differences in attention control or secondary memory. Future research is needed to better examine how other span measures can be accounted for by multiple factors and whether these multiple factors account for the relations among the span measures themselves and with higher-order cognition.

Based on the multifaceted view of WM, the current results suggest that, at least, three separate factors drive performance in working memory tasks and give rise to individual differences in working memory. Naturally one question is whether these results suggest that complex span tasks simply have poor construct validity. That is, are complex span tasks bad measures because they reflect multiple factors? We believe the answer is No. Rather than suggesting that complex span measures are poor indicators of WM, the current results suggest that the overall WM system is multifaceted and made up of several important processes. Thus, complex span measures are actually valid indicators because they pick up variance from each of these important processes. That is, no task is a process pure measure of the construct of interest; rather performance on any measure reflects the joint interaction of several processes. As such WM measures reflect the joint interaction of several processes that are needed for accurate performance. Thus, these results demonstrate that complex span measures reflect these separate factors which accounts for variability across individuals. This finding is not necessarily unique to the complex span measures. For example, consider the change detection measures used in the current study. These measures likely reflect individual variation in the number of things that can be distinctly maintained (i.e., capacity; Cowan et al., 2005) as well as individual differences in the ability to control attention and filter out irrelevant information and prevent attentional capture (Fukuda &

Vogel, 2009, 2011; Vogel, McCollough, & Machizawa, 2005). The fact that the capacity and attention control factors were so highly correlated is evidence that these two factors are strongly linked and provides evidence that change detection measures likely reflect both. Furthermore, recent research has suggested that these change detection measures also partially measure individual differences in secondary memory (Shipstead & Engle, 2013). Thus, like complex span measures, this suggests that change detection tasks measure variation in all three factors, but differ in the extent to which any factor drives performance (with secondary memory playing less of a role than capacity and attention control). Additionally, the current results suggest that gF measures also reflect several separate sources of variance (Detterman, 1994; Jensen & Wang, 1994). As shown in Fig. 7, the gF construct is made up of several different sources of variance. Thus, like measures of WM, gF also seems to be a multifaceted construct. These results point to the need to examine multiple joint influences on variation in a number of cognitive constructs and suggest that individual differences are due to multiple factors even within a particular construct.

5.3. Other important processes

Thus far we have argued that capacity, attention control, and secondary memory are three important processes of WM. However, it would be remiss not to point out that other processes are also likely important for WM and likely covary with capacity, attention control, and secondary memory retrieval. For example, these other processes would include integration and coordination processes that are specifically needed in WM where processing and storage operations are combined (Bayliss et al., 2003; Oberauer, Süß, Wilhelm, & Wittmann, 2003), updating and attention switching operations that are more likely needed in complex span tasks (Oberauer, 2002; Unsworth & Engle, 2008; Verhaeghen & Basak, 2005), as well as binding operations that are needed to momentarily bind items (Halford, Cowan, & Andrews, 2007; Oberauer, 2005). Each of these proceses has been linked to WM in the past and each has been suggested as possible reasons for the strong relationship between WM and gF. Clearly more work is needed to determine the extent to which these processes (as well as potentially other processes) are related with capacity, attention control, and secondary memory, as well as whether these other processes are needed to fully account for individual differences in WM and the relation between WM and gF.

6. Conclusions

Collectively, the current results are very much in line with the multifaceted view of WM, suggesting that WM is a system composed of distinct and interacting processes. In particular, individual differences in capacity, attention control, and secondary memory jointly account for individual differences in WM and its relation with gF. Thus, the current results help resolve debates about "the" reason for the relation between WM and gF. The current results strongly suggest that multiple mechanisms drive the relation between WM and gF. In order to understand the nature of WM and why WM strongly predicts individual differences in gF we must attempt to understand the multifaceted nature of WM and understand how these various mechanisms independently and jointly lead to variation in host of higher-order cognitive activities.

Acknowledgment

Thanks to Tom Redick and three anonymous reviewers for helpful comments on an earlier version of the article.

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