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Individual Differences in Attention Control

Implications for the Relationship Between Working Memory Capacity and Fluid Intelligence

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In this chapter, we detail our approach to the study of individual differences in working memory capacity (WMC) and how it has contributed to understanding the mechanisms of complex cognition. Theories of working memory have primarily focused on specifying how information is represented and manipulated in a limited-capacity cognitive system. Individuals differ in the efficacy of their working memory systems, forming the basis for WMC as a psychometric construct. Decades of research have shown that WMC is predictive of a broad range of abilities and outcomes (Engle, 2002; Engle & Kane, 2004; Feldman-Barrett, Tugade, & Engle, 2004). One of the most robust and, we believe, important findings is that WMC strongly predicts fluid intelligence (Gf), the ability to solve novel problems and learn new information (Kane, Hambrick, & Conway, 2005; Kyllonen & Christal, 1990). A central feature of many models of the working memory system is a domain-general executive attention, sometimes called a central executive, which regulates other components of the system (Baddeley & Hitch, 1974; Cowan, 1999). We argue that this attentional component forms the basis of the WMC–Gf relationship.

Let us begin by placing WMC within the context of a more general framework in order to understand why it is so broadly predictive. Few notions in psychology have as much theoretical utility as the distinction between automatic and controlled processing. Psychological theories that adopt this distinction are known as dual-process theories, and many theories of cognition are amenable to this outline. Norman and Shallice (1986), for example, developed a framework in which actions are automatically activated given an individual's current goals in some current context. Many action sequences can be performed this way, without need for conscious awareness or investment of conscious attention. However, situations arise in which actions selected by automatic processes are not appropriate or optimal. In such cases, the readily available response must be resisted in favour of a more effortful, controlled, and generally conscious, mode of responding. In the Norman and Shallice (1986) model, this is when the supervisory attention system becomes important. The supervisory attention system influences the selection of action schemas when the automatically activated schematic response is inappropriate, when there is conflict between activated schemas, or when a situation is novel and no schematic response is available (Norman & Shallice, 1986).

C7.T1 **Table 7.1** Summary responses to designated questions

Question	Response
1. Definition of working memory	We define working memory as the cognitive system that permits the maintenance of goal-relevant information. More structurally, working memory comprises domain-general executive attention coupled with domain-specific short-term memories. We regard short-term memory as those aspects of long-term memory residing above some activation threshold, making them available or potentially available to influence ongoing cognition, as well as those processes necessary to keep this activation above threshold (e.g. subvocal rehearsal).
2. Methodology	Our group has focused on the use of large, broad-ability samples to study aspects of cognition at the latent construct level. We are interested in the role of different aspects of working memory in real-world cognition and how what we learn in the laboratory can be extended to real-world tasks. The advantage of our methods is that they avoid the mistakes of thinking that a single task can reflect a construct, that 'mean performance' reflects all the people in the sample, and that data collected from college sophomores reflects cognition in all people. The disadvantage is that these methods are very time-consuming and very expensive.
3. Unitary versus non-unitary nature of working memory	Working memory is at least non-unitary to the extent that it consists of both attention and memory processes. Attention is unitary. We believe that there is one 'attention' that cannot be divided but can be switched back and forth between tasks quickly. This switching puts a premium on temporary maintenance of information from each task being switched between. Performance will be degraded when information for one task is lost/degraded while attention is directed at a different task. The resulting temporary memories are domain specific and, depending on the similarity of the domains, will vary in how they interfere with one another.
4. The role of attention and control	One possible concern with our use of 'executive attention' is that of the homunculus (in the Skinnerian sense). One might charge that we are not really saying that much about how executive attention might function, but instead are simply appealing to it as some mystical cognitive arbiter. We think that such a criticism misses the point. While we have often abstained from theorizing about the implementation and operations of executive attention, we do not regard it as remotely similar to a little man in the head. Rather, our work typically aims to understand the individual differences in cognitive abilities and what patterns of variation can tell us about the relationships between constructs. Such theorizing is thus tangential to our goal. All the same, readers of our work may suspect us of simply falling back onto a homunculus. To those readers, we point out that many explicit computational systems behave as though they might have a homunculus operating behind the scenes. For example, the computer programs Watson and Deep Blue operate as though they were inhabited by the world's best *Jeopardy!* and chess players, but the computations underlying their superb performance in these domains are completely specified. Thus, this is a good question for philosophers to sit with, but not one we are willing to become paralysed by.

Table 7.1 Continued

Question	Response
5. Storage, maintenance, and loss of information in working memory	We approach working memory via the study of attention, and so have been less interested in studying hallmark effects of working memory coding and storage, such as the word length effect, than in studying the ramifications of individual differences in executive attention for working memory and its relationship to complex cognition and real world behaviour. Indeed, the complex span tasks, which have been instrumental to the study of WMC, attempt to disrupt the rehearsal processes responsible for such effects in order to isolate the effects of executive attention. In our view, interference rather than decay is the primary reason for (unintended) loss of information in working memory. For supporting evidence, damage to the prefrontal cortex leads to impaired memory performance only when there is opportunity for interference (Della Salla, Cowan, Beschin, & Perini, 2005). Without interference, temporal delay had little effect. Our view also regards loss of information from working memory as, at times, intentional, adaptive, and requiring of attention, which we term 'disengagement'. The sensitivity of fluid intelligence (Gf) measures to disengagement processes accounts for the strong relationship between WMC and Gf.
6. What is the relationship between working memory, long-term memory, and learning?	Working memory is important for learning because it holds representations active in memory so that elaboration and integration with related representations in long-term memory can occur (c.f. Craik & Lockhart, 1972). This may create the impression that expertise increases memory capacity because 'more' can be held active in memory at one time (Chase & Simon, 1973). This has been explained via chunking, but it is less clear how 'chunking' occurs or why larger chunks do not require more resource investment despite containing more information (e.g. lists of differing length do not differ in retrieval time; Conway & Engle, 1994). Speculatively, one way this could obtain is that what is held active in memory are not representations per se but rather 'address tags' to a representation's location in long-term memory. Thus, the function of working memory would not be to contain representations, but rather to keep representations readily accessible. The result is an increase in the amount of information available to the working memory system (by virtue of more elaborated representations) without greater resource expenditure. For example, if one were tasked with summarizing their five favourite novels, the relevant information would surely exceed the limited capacity of working memory. Even so, by virtue of having a memory tag for *Crime and Punishment* active in working memory, one could report that the story follows the moral tribulations of Rodion Raskolnikov, expound upon the details, causes, and outcomes of said tribulations, and repeat the process for the other four novels. All of the pertinent information is not contained in working memory at the same time, but is made readily available by the working memory system. This notion is very different from the idea of working memory training, the idea that training working memory to have a larger capacity should increase Gf. This simply is not the case (Redick et al., 2013). This is sensible in our framework because we do not assume a causal relationship between WMC and Gf.

Table 7.1 Continued

Question	Response
7. Is there evidence that is not consistent with your theoretical framework, and how does your framework address that inconsistency?	Periodically, researchers have approached us claiming that they cannot replicate results from our studies. Upon further discussion, many of these replication attempts suffer from small samples and/or restricted ability ranges, both of which are fatal to correlational and regression-based analyses leading them to accept the null hypothesis. Other researchers who have avoided these pitfalls consistently replicate our work. At other times, we have blatantly disagreed with other researchers about how best to interpret a pattern of results. In many such cases, the difference of opinions is rooted in fundamental disagreements about how best to frame and/or measure a construct (e.g. the nature of WMC or the unitary nature of attention control). The simple fact that work is ongoing means that different researchers are in all likelihood blindly grasping at different parts of the same elephant. In dealing with this friction, we try to take seriously the criticisms of researchers with whom we respect and happen to disagree and who are working on similar topics. We try to incorporate these into ideas for future studies. In evaluating differences of opinion, we begin by considering psychometric factors associated with tasks and their use with certain samples and proceed from there.
F. Working memory applications	Our recent work has confirmed that WMC is highly predictive of success in a vast array of real-world contexts, including multitasking (Redick et al., 2016) and in detecting fatigue (Lopez, Previc, Fischer, Heitz, & Engle, 2012). However, it is important to not overstate its importance, and our recent thinking is that WMC serves a complementary function to Gf. The tasks used to measure WMC reflect primarily maintenance of information while the tasks used to measure Gf reflect the function of disengagement from information or goals no longer useful for the current task. The high correlation between WMC and Gf is due to the fact that both constructs rely on domain-general executive attention. Thus, we can better understand complex cognition by trying to understand the relative contributions of WMC and Gf to successful behaviour, and by exploring the relative predictive utility of tasks reflecting WMC, Gf, and executive attention within a domain of interest (see Martin et al., 2019 for an example of this applied to reading comprehension).

Research on the functional organization of attention in the brain also seems interpretable in a dual-process framework. Several isolable attention networks have been distinguished, namely the orienting, alerting, and executive networks (Fan, McCandliss, Sommer, Raz, & Posner, 2002). The alerting and orienting networks enact automatic stimulus selection and the executive network resolves interference or conflict between competing stimuli and/or potential responses. Other examples abound (Greenwald & Banaji, 1995; Kahneman, 2011; Spelke, Hirst, & Neisser, 1976). There are thus echoes of the automatic/controlled processing distinction in many widely known and accepted theories in cognitive psychology, cognitive neuroscience, and cognitive science.

C7.P3   We have argued that individual differences in WMC, defined as the ability to use attention to maintain items in memory in the face of distraction or interference, reflects individual differences in controlled processing (Feldman-Barrett et al., 2004). The fact that controlled processing becomes relevant over large swaths of human activity would

thus account for the broad predictive validity of WMC. However, we now believe that it is not WMC per se that underpins variation in controlled processing. Rather, the lynchpin is the more general ability to deploy attentional resources to dynamically manage ongoing cognition.

C7.P4   We believe that research on the relationship between WMC and Gf suggests two broad, interacting control mechanisms: maintaining goal-relevant information in memory and disengaging from outdated or irrelevant information. Before discussing our recent theoretical advancements, we outline the development of the executive attention theory of WMC. We then summarize our recent extensions of the theory and show how it explains the relationship between WMC and Gf. Along the way, we highlight ongoing methodological and theoretical issues and some of our own missteps that should be instructive for other researchers.

C7.S1   ## Working Memory Capacity as Executive Attention

C7.S2   ### Simple and Complex Span Tasks Are Clearly Different

C7.P5   The executive attention theory of WMC stems from research comparing individual differences on simple memory span and complex memory span procedures. Simple memory spans, such as the digit span, present participants with a set of to-be-remembered items that must be recalled (the order of recall varies by procedure) and comprised much of the early work on short-term memory. A participant's memory span is traditionally operationalized as the list length above which memory errors occur or as the total number of correctly recalled lists of variable length (assuming that errors are fairly constrained to longer, more difficult lists). A short-term memory store, construed as a passive, limited-capacity buffer, was a core component of many early multistore models of human memory, typified by the modal model (Atkinson & Shiffrin, 1968; Engle & Oransky, 1999). Crowder (1982) attempted to retire short-term memory as a theoretically useful construct, partly based on the inability of simple span tasks to predict complex cognition (e.g. Perfetti & Lesgold, 1977; Turner & Engle, 1989). Given the centrality of the short-term store to theories of human memory, surely its limitations should be broadly predictive—that they were not was troubling. Subsequent models of working memory complicated the short-term store substantially, emphasizing not just the storage of information, but the active processing of stored information (e.g. Baddeley & Hitch, 1974). Complex spans were designed with these more complicated working memory models in mind. They, too, present participants with to-be-remembered items, except participants must perform a processing task after each item is presented (Fig. 7.1). At some point, participants are prompted to recall the presented items in their correct serial position. Compared to the simple span procedure, complex span procedures have proven immensely fruitful.

C7.P6   The first complex span task, the reading span, was developed by Daneman and Carpenter (1980). Daneman and Carpenter had participants read a variable number

Operation span

Symmetry span
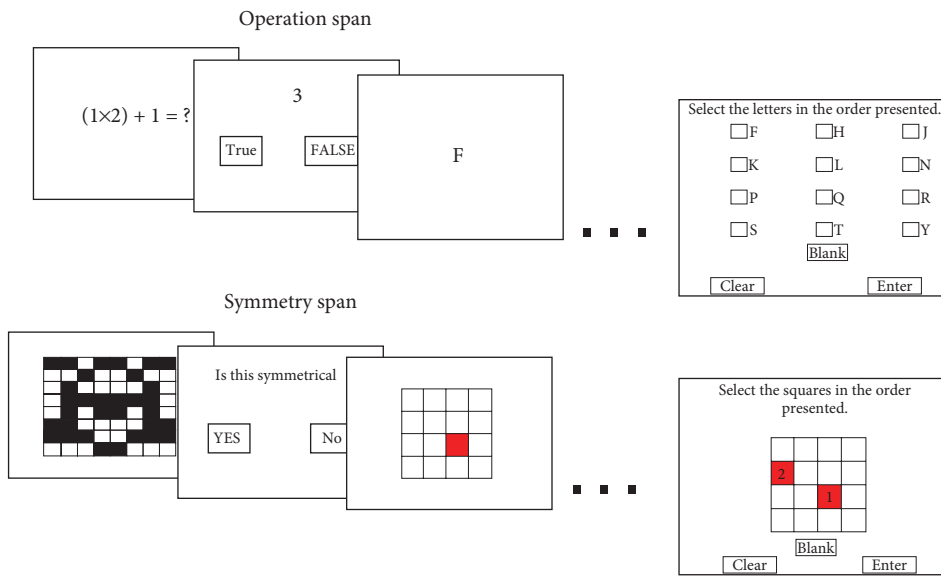
C7.F1   **Fig. 7.1** Examples of complex span tasks. In the depicted version of the operation span (top panel), subjects solve simple equations and are given letters to remember. After a variable number of equations (usually two to eight), participants are cued to recall the letters in their correct forward serial position. The symmetry span follows the same scheme except participants make symmetry judgements about a visual pattern and are tasked with remembering highlighted cells in a 4×4 grid. The operation and symmetry spans concern memory for verbal and visuospatial material, respectively.

of sentences. Afterward, they were cued to recall the last word of each sentence in its correct serial position. In contrast to a simple word span, the number of items correctly recalled in the reading span was highly predictive of reading comprehension. Daneman and Carpenter originally attributed the correlation between reading span performance and reading comprehension to reading skill: strong readers outperformed poorer ones because they expended fewer resources while reading the sentences, leaving more resources available for actively retaining the memoranda. Turner and Engle (1989) expanded this finding, showing that the relationship between complex span performance and higher cognition is a great deal more general than Daneman and Carpenter suspected. They substituted the sentence reading task with solving simple mathematical problems (e.g. top of Fig. 7.1). This mathematical operation span predicted reading comprehension as well as the reading span did, suggesting that reading skill could not account for the reading span's predictive power. While they did not find an effect of the domain of the processing task, Turner and Engle did find that more difficult processing tasks lead to better differentiation between good and poor readers, regardless of processing domain. This suggested that the amount of processing resources available to the working memory system may be an important component of what complex spans measure. In contrast, simple spans did not correlate with reading comprehension.

C7.P7   Pursuing this line of thought further using latent variable analyses,[1] Engle, Tuholski, Laughlin, and Conway (1999) conducted a study differentiating short-term memory (as measured by simple span tasks) from WMC (as measured by complex span tasks) and tested their relationships with Gf. They administered numerous measures of short-term memory, WMC, and Gf to a sample of undergraduates[2] and submitted the data to a series of factor analyses and structural equation models. Prior theory fractioned the working memory system into mechanisms providing storage plus an attentional component coordinating the processing of stored information (Baddeley & Hitch, 1974; Cowan, 1988). Based on this work, Engle et al. (1999) expected substantial overlap between short-term memory and WMC latent factors due to the common influence of short-term storage, but the factors should have been distinguishable due to attention-related variance in the WMC factor. Indeed, a model positing separate short-term memory and WMC latent factors fits the data better than a model positing a single memory factor. These separate factors related differentially to Gf. In a model with WMC and short-term memory each predicting Gf, short-term memory added no predictive value above that already accounted for by WMC. Finally, under the assumption that WMC is comprised of short-term memory storage plus controlled attention, the shared variance between the WMC and short-term memory latent factors was extracted. This factor was thought to reflect short-term memory storage. The WMC residual, meanwhile, was thought to mainly reflect variance associated with executive attention. Both sources of variance were significant predictors of Gf, with the attention-related WMC residual accounting for the bulk of prediction. This suggests that attention is relatively more important for predicting Gf than short-term memory.

C7.P8   Engle et al.'s (1999) findings were promising, but WMC remained underspecified. Many theorists assumed that WMC was a unitary domain-general construct, but it remained possible that it could be decomposed into modality-specific control processes. For example, prior work suggested little overlap between working memory tasks of different modalities (e.g. verbal and visuospatial working memory; see Fig. 7.1; Shah & Miyake, 1996). This finding was sensible to the extent that verbal and visuospatial working memory tasks make use a different coding schemes and representational formats, and perhaps even different storage systems (Baddeley, 1986; Baddeley & Hitch, 1974; Crowder, 1982). However, methodological concerns with prior work (e.g. homogeneous sampling with regard to cognitive ability leading to likely underestimation of attentional processes) and the widely held theoretical unity of attention control led Kane et al. (2004) to test the generality of WMC. They administered a battery of verbal

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[1] Latent variable analyses are a group of advanced statistical techniques including exploratory factor analysis, confirmatory factor analysis, and structural equation modelling (among others) that are used to study unobserved constructs based on the patterns of variation and covariation within a set of observed variables. Performance on individual tasks is determined by numerous processes, making them difficult to interpret. Latent variable analyses mitigate this problem by modelling the variance shared by a group of measures purporting to index some common construct important to each. This gives us a much better measure of the processes we are interested in measuring because variability specific to individual tasks is partialled out.

[2] Most other studies discussed in this chapter had samples consisting of individuals recruited from universities as well as the surrounding community.

and visuospatial short-term (simple span) and working memory (complex span) tasks as well as measures of verbal, spatial, and matrix reasoning. Examination of zero-order correlations suggested stronger interrelationships among their working memory tasks than among their short-term memory tasks, a finding corroborated by an exploratory factor analysis that converged on a solution with a single WMC factor and separate verbal and visuospatial short-term memory factors. A more conservative confirmatory factor analysis, meanwhile, revealed that the best-fitting solution to the data was a four-factor solution with separate but related factors for both verbal and visuospatial short-term memory and WMC. Notably, while the verbal and visuospatial short-term memory factors correlated at 0.63, the WMC factors correlated at 0.83. This confirmed that WMC is a more general concept than short-term memory, and we contend this is due to the influence of individual differences in a domain-general executive attention. The disunity in WMC we attribute to contamination by domain-specific storage processes. If we are correct, the variance common to all the measures should provide a fairly pure measure of attention control; consistent with Engle et al. (1999)'s findings, it strongly predicted Gf.

Simple and Complex Spans: Not So Different After All?

Despite many demonstrations of simple spans' failure to account for variation in complex cognition, some studies do in fact report relationships with Gf on par with complex spans (La Pointe & Engle, 1990). For example, Colom and colleagues (Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2005; Colom, Abad, Rebollo, & Shih, 2008) contend that simple and complex spans are virtually indistinguishable in the processes that they measure. These results seem difficult to square with studies showing a clear distinction (Daneman & Carpenter, 1980; Engle et al., 1999; Turner & Engle, 1989). Though initially puzzling, results from Unsworth & Engle (2006, 2007b) suggest differences across studies in simple span scoring procedures may be to blame for the discrepant findings. Plotting correlations between complex span performance and Gf as a function of memory set size, Unsworth and Engle (2006) found fairly stable correlations, even for small set sizes (see also Salthouse & Pink, 2008). Correlations between simple spans and Gf, on the other hand, were weak at smaller set sizes but rivalled complex span correlations at longer list lengths. Unsworth and Engle (2007b) argued that typical methods of scoring simple spans (e.g. summing the number of correctly recalled lists) disregard important variation in longer list lengths where errors become common. In several re-analyses of published data that initially asserted a hard distinction between simple and complex span tasks, simple spans showed correlations of similar magnitude to complex spans when the proportion of all correctly recalled memoranda was used as the estimate of memory span rather than the more stringent correctly recalled-lists criterion. Theoretically, the two methods should yield very similar correlations with Gf up to an individual's capacity for passive online memory storage. However, individuals vary with how many errors they make once this limit is surpassed. The proportion-correct

method is sensitive to this variation, allowing individual differences in the recall of longer lists to contribute to the final memory span score. The correctly recalled-lists method effectively ignores this variation, since errors become common after the passive storage capacity is exceeded. When the proportion-correct scoring method was used for scoring simple spans and separate complex and simple span factors were included in a structural equation model, neither added uniquely to the prediction of Gf; the two classes of tasks were virtually isomorphic at the latent level (Unsworth & Engle, 2007b).

C7.P10   Outlining the processing and storage operations that occur while participants complete the tasks can help explain inconsistencies in the relationship between simple and complex spans. In recent work, we have adopted the primary memory/secondary memory terminology for discussing memory storage. Primary memory consists of currently activated portions of long-term memory that are immediately available for use by the cognitive system (a similar idea to what is usually meant by 'short-term memory'). Secondary memory is comprised of the portion of long-term memory activated below some critical threshold and not readily available for use (Conway & Engle, 1994; Shipstead, Lindsey, Marshall, & Engle, 2014; Waugh & Norman, 1965). The amount of information that can be kept active in primary memory is severely constrained (Cowan, 2001; Cowan et al., 2005; Waugh & Norman, 1965). Information in that active primary memory state will decline in activity over time due to interference or decay (primarily interference; see Nairne, 2002). Keeping it 'active' requires it be reactivated by the spotlight of attention before it falls below a threshold we think of as reflecting consciousness. In complex span tasks, to-be-remembered items compete with a processing task for activation in primary memory. As representations of memoranda lose activation, they risk being lost from primary memory though, of course, they would still be represented in secondary memory. Attentional resources must be diverted to maintain these items at some supra-threshold level of activation, or to conduct a constrained search of secondary memory based on available retrieval cues. Attention control is required to conduct this search most effectively (Unsworth & Engle, 2007a). When list length is sufficiently long to force competition among items in primary memory, simple span procedures will also place demands on primary memory maintenance and secondary memory search. This, we argue, accounts for the uniform correlation between complex spans and measures of Gf, while the relationship with simple spans varies as a function of list length.

C7.P11   Short-term memory and WMC measures thus exist on a continuum, a continuum which need not be graded uniformly across members of different populations. A simple span may be a short-term memory indicator for a cognitively healthy young adult, but will require significantly greater attentional resource investment from a similar young adult with executive dysfunction (Perry et al., 2001) or a cognitively healthy child (Bayliss, Jarrold, Baddeley, & Gunn, 2005). In these latter cases, a simple span may fairly be called a measure of WMC in that it involves an investment of limited-capacity attention. A similar point pertains to complex spans. For example, the operation span does a poor job discriminating between high-ability participants (Draheim, Harrison,

Embretson, & Engle, 2018). One explanation for this poor differentiation is that higher-ability participants are more likely to have extensive exposure to basic mathematics and arithmetic operations. Solving simple equations may be much more automated for them than for a lower-ability participant with less mathematical proficiency (Turner & Engle, 1989). This may allow high-ability participants to direct more attentional resources to retaining memoranda, thereby limiting variability in the number of correctly reported letters (c.f. Conway, Cowan, & Bunting, 2001; Underwood, 1974). The operation span may thus tap more storage-related (i.e. short-term memory) variance than other complex spans when used in high-ability samples. None of this is to say that short-term memory and working memory are not meaningfully distinct constructs. We still regard short-term memory as providing memory storage and working memory as comprising short-term memory plus attention control. We merely wish to stress that one cannot be confident that they are measuring one construct or the other based on the class of task used alone. The crucial difference between short-term and working memory has less to do with the kind of task used and more with what participants must do to complete said task.

C7.P12   Though the preceding discussion fixates heavily on complex spans, the reader should not interpret this as our endorsing them as the only way of measuring WMC. As we show later, our recent theorizing has been greatly impacted by considering other more dynamic classes of measures, such as the running memory span and *N*-back, which sometimes show larger correlations with Gf than do complex span tasks (Broadway & Engle, 2010; Shipstead, Harrison, & Engle, 2016; Wilhelm, Hildebrandt, & Oberauer, 2013). Thus, while complex span tasks have been a fixture of our programme of research, our current theorizing also takes into account other classes of WMC measures and their relations to attention control and Gf.

C7.S4   ## Direct Evidence for the Working Memory Capacity–Attention Control Relationship

C7.P13   Many of these early studies assumed that variance unique to complex span tasks reflected attention control without actually measuring attention control, leaving the door open to alternative explanations of the relationship between Gf and WMC. More direct approaches were thus required to establish an association between WMC and attention control. Confirmatory evidence for this relationship initially came from quasi-experimental designs comparing the performance of individuals deemed high and low in WMC. These studies typically screened a large sample of participants on a WMC measure and divided the sample into tertiles or quartiles based on their scores. The highest and lowest scoring groups were deemed high- and low-spans, respectively, and their performance on established attention control tasks was compared. If attention control were at all predictive of WMC, span differences should be apparent whenever a task requires controlled processing.

C7.P14   One task featured prominently in our work and in the field at large is the anti-saccade task (Everling & Fischer, 1998). In this task, participants are presented with a central fixation cross followed by a briefly presented cue on the right or left side of the screen. A typical anti-saccade task consists of two trial types which can be presented either in separate blocks or mixed within a block. On pro-saccade trials, participants must orient their gaze towards the peripheral cue in time to identify a target presented after the cue but in the same location. The target is masked a brief time later. Orienting towards changes in the environment (e.g. movement) is an evolutionarily ingrained pre-potent response. As such, participants could presumably perform well based on reflexive responding alone. Anti-saccade trials follow the same scheme as pro-saccade trials, except the to-be-identified target appears opposite the peripheral cue. Participants must use the peripheral cue as an indication of where *not* to look. This requires them to resist the automatic predisposition to orient towards the cue, lest they miss the target appearing on the other side of the screen. Anti-saccade trials thus force controlled processing by rendering an automatic response incompatible with current goals. Attention control is necessary for overriding the automatic tendency and supplementing it with a novel goal-appropriate response (c.f. Norman & Shallice, 1986).

C7.P15   Kane, Bleckley, Conway, and Engle (2001) showed span differences in anti-saccade task performance. Participants were divided into upper and lower WMC quartiles based on their operation span scores and their performance on pro-saccade and anti-saccade blocks was compared. To reiterate, span differences were expected on anti-saccade trials, because performing well requires participants to avoid reflexively looking at the peripheral cue and to instead make a goal-appropriate saccade in the opposite direction. Span differences were not expected on pro-saccade trials because looking towards motion is an automatic response. The expected pattern emerged. High-spans were more accurate on anti-saccade trials and responded more quickly than low-spans. High- and low-spans did not differ on pro-saccade trials when they preceded an anti-saccade block. Interestingly, span differences *did* emerge on pro-saccade trials when the anti-saccade block came before the pro-saccade block, with low-spans being slower and more error-prone on pro-saccade trials. This pattern hinted that low-spans tended to perseverate on task goals, a common symptom of frontal lobe damage and executive dysfunction (Kane & Engle, 2002). Across every metric considered, high-spans demonstrated better attention control abilities than did low-spans.

C7.P16   Results from Unsworth, Schrock, and Engle (2004) replicated and extended these findings. They investigated span differences in anti-saccade performance without a target identification requirement; participants merely needed to initiate a saccade in the appropriate direction, saccades were measured with an eye tracker. Across several task configurations, they demonstrated that span differences on anti-saccade trials consistently emerge, such that high-spans were less likely to initiate a saccade towards the peripheral cue. They even found that span differences on pro-saccade trials can be induced by introducing control demands on these trials. If low-spans tend to perseverate on current goals, then requiring them to dynamically update their current task set should put them at a disadvantage; for example, switching between the goal to initiate

a saccade in the opposite direction as a cue (anti-saccade) and the goal to initiate a saccade in the same direction as a cue (pro-saccade). Indeed, low-spans were now slower to initiate a correct pro-saccade when pro-saccade and anti-saccade trials were mixed within a single block. High-spans' consistent, systematic advantage on the anti-saccade task supports our earlier conjecture that individual differences in attention control contribute to variation in WMC.

C7.P17   The results from Kane et al. (2001) and Unsworth et al. (2004) provide some indication that, at least for the anti-saccade task, differences in WMC become important whenever executive control processes are engaged. Particularly important is the instantiation of goals in memory (Meier, Smeekens, Silvia, Kwapil, & Kane, 2018). We have advanced similar arguments about performance in the Stroop task in which subjects must resist the automaticity of reading a colour word to name the colour in which it is printed (e.g. seeing the stimulus GREEN and having to respond with the word 'Blue'; Kane & Engle, 2003), but WMC is predictive of a wide range of attentional phenomena. For example, Heitz and Engle (2007) investigated individual differences in the ability to narrow the focus of attention to the central target in an arrow flanker task.[3] High-spans were faster to constrain their focus to the target, thereby mitigating the influence of peripheral distractors earlier than did low-spans. Bleckley, Foster, and Engle (2015) presented low- and high-span participants with parallel bars running the length of two sides of a square display. A square target was cued to appear at the end of one bar, and participants were instructed to press a key when the target appeared. However, the cue only predicted the target location 75% of the time. On the remaining 25% of trials, the cue could either appear on the opposite end of the cued bar (within an object) or on the corresponding area of the parallel bar, with both being equidistant from the actual cued location. High-spans were faster to react to the cue on invalidly cued trials when the target appeared within an object than when it appeared in the corresponding area of the other bar. For low-spans, the location of the target did not matter; they were equally slow whether the target appeared within- or between-objects relative to the invalid cue. This pattern suggests that high-spans may be more likely to attend to objects where low-spans are more likely to attend to locations. Importantly, putting high-spans under cognitive load impairs their ability to engage in object-based attention, making their performance mirror that of low-spans (Bleckley et al., 2015). High-spans thus exhibit greater efficiency and flexibility in how they allocate their attentional resources while low-spans are slower and more rigid.[4]

C7.P18   WMC predicts an array of attentional phenomena, lending support to the position that complex span performance is influenced by individual differences in attention control. This conclusion is made even more tenable by noting the minimal memory storage demands imposed by many attention control measures. For example, each trial

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[3] Participants see strings of arrows and indicate the location of the central arrow. The central arrow can either be congruent with the others in the series (← ← ← ← ←) or incongruent (← ← → ← ←), and the flanker interference effect is calculated as the mean reaction time on incongruent trials minus the mean reaction time on congruent trials.

[4] Though the studies outlined thus far have been primarily concerned with visual tasks, WMC also predicts attention performance in various auditory domains, including dichotic listening (Conway et al., 2001).

type on the anti-saccade is defined by at most a single critical instruction, to look towards or away from the peripheral cue (Roberts et al., 1994). This is well within the limits of online memory storage (Cowan, 2001), making memory load an unlikely contributor to span differences.

C7.P19   The quasi-experimental studies reviewed earlier have been instrumental to our thinking about individual differences in WMC, but they have several undesirable features. For one, they ignore scores towards the middle of the WMC distribution, making it difficult to assess effect size. These studies establish an association between attention control and WMC, but they cannot speak to the magnitude of the relationship. Additionally, while these quasi-experimental results are consistent with our theoretical framework and we assume that span differences in attention control tasks map on to intelligence differences, these studies do not actually measure Gf. More importantly, the extreme-groups design suffers from a basic issue of interpretation. We grouped participants based on their scores on one or more WMC tasks, but the fact that WMC and Gf are so highly correlated means that high-WMC individuals were likely high-Gf individuals. Therefore, we do not know whether the results were due to differences in WMC, Gf, or some third variable. This difficulty is elaborated further in the later section on maintenance and disengagement theory. Although we and others have expressed reservations about the interpretive difficulties associated with extreme-groups designs (Engle, 2018; Engle & Martin, 2019; Wilhelm et al., 2013) and we instead opt for large-sample factor-analytic and structural equation modelling studies in our more recent work, the fact that high- and low-spans differ on attention control tasks despite their minimal memory load is instructive, and any theory of WMC must account for this relationship.

Relating Variation in Working Memory Capacity to Fluid Intelligence

C7.S5

C7.P20   The preceding sections outlined the theoretical account of individual differences in WMC that we have been advancing since the 1990s, and sparing a few substantial elaborations, this is how we still think about WMC. Numerous investigations all point to the conclusion that controlled attention contributes substantial variance to WMC, and accounts for WMC's broad predictive power. Though it has been challenged, we find that the major tenets of the executive attention theory remain quite tenable, and other researchers are converging on similar views (Friedman & Miyake, 2017; Gathercole et al., 2008; Gray et al., 2017; Kaufman, Schneider, & Kaufman, 2019; McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Rueda, 2018). The theory has not remained unchanged, however and many of the revisions to our position have resulted from greater specification of the mechanisms relating WMC to Gf, predominately by their mutual dependence on attention control for regulating the contents of memory.

C7.P21   A study by Shipstead et al. (2014) segues nicely into our recent thinking. Shipstead et al. sought to explain the relationship between WMC and Gf by way of attention

control and its interface with memory systems. They derived latent factors thought to reflect variance associated with primary memory, secondary memory, attention control, and Gf. They also formed WMC factors from several different kinds of tasks, including complex spans, running memory spans, and visual arrays tasks.

C7.P22   Brief treatments of the running memory span and visual arrays tasks as measures of WMC are needed before discussing Shipstead et al.'s results. Tasks like the running memory span (and others that combine storage and processing demands) typically show equivalent or slightly stronger relationships with Gf than measures that separate storage and processing (Broadway & Engle, 2010; Cowan et al., 2005; Shipstead, Redick, Hicks, & Engle, 2012). Where complex spans separate storage and processing functions, running memory spans require participants to perform storage and processing operations on the same items in memory. For example, participants may be presented with a long but variable string of letters, but will only be asked to report the last several. This requires participants to continually update the contents of primary memory. Complex span tasks, meanwhile, require participants to maintain to-be-remembered items in primary memory without further processing. Items that fall below a critical activation threshold must be retrieved from secondary memory. Complex spans thus tap primary memory to some degree, but also secondary memory. However, the running memory span's integrated storage and processing demands may provide a more comprehensive measure of a person's ability to dynamically manage the contents of primary memory. If managing and updating the contents of primary memory is important for performing well on Gf tests, this could explain their particularly strong relationship with tasks like the running memory span.

C7.P23   Another class of tasks used to measure WMC are the visual arrays, or change detection, tasks (Luck & Vogel, 1997). In a typical visual arrays task, participants are presented with a fixation, followed by a target array containing stimuli of differing colours, shapes, and/or orientations. This target array is removed and a test array is presented after a brief inter-stimulus interval. Depending on the version administered, participants must either indicate whether a cued item in the test array has changed from the target array or whether any item in the test array differs from the initial target. Though widely regarded as measures of static online primary memory storage capacity (Cowan et al., 2005; Luck & Vogel, 1997), evidence suggests that other processes are important for visual arrays performance. For example, visual arrays capacity estimates predict a person's susceptibility to attentional capture (Fukuda & Vogel, 2009, 2011) and varying the interval between trials modulates the build-up of proactive interference, suggesting a role for secondary memory retrieval (Shipstead & Engle, 2013). Visual arrays performance is thus more multiply determined than is typically assumed.

C7.P24   Shipstead et al. (2014) varied the attention control demands of their visual arrays tasks. On some versions, participants were cued to ignore a subset of items presented in the target array (Fig. 7.2c, d). For example, in Fig. 7.2d, a participant sees an assortment of red and blue rectangles in the target array with the instructions to attend to one of the colours (blue, in this case). On the test array, one of the attended elements is cued and the participant must indicate whether that element has changed in orientation
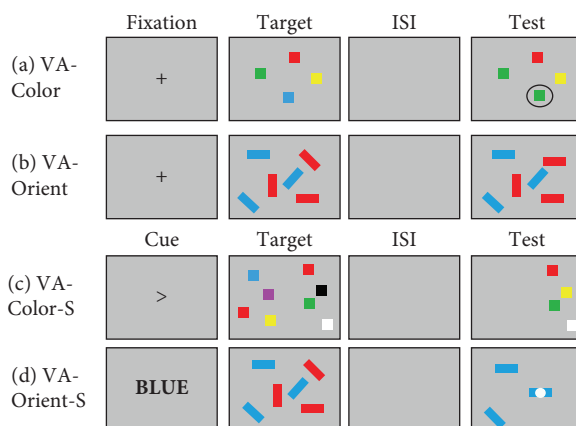
Fig. 7.2 Examples of visual array (VA) tasks used by Shipstead et al. (2014). The labelling of each task is based on the following criteria: VA-[the category of the change-based judgement]-[is there a selection component]. The two potential judgements for change are colour or orientation (i.e. has a square changed colour, or has a bar changed orientation). The selection components direct an individual to pay attention to half of the array (either one side (the right or left subset) or one subset of stimuli (blue or red bars only)). In panel (a), the test-taker must indicate whether the encircled box has changed colours. In panel (b), the test-taker must indicate whether any box has changed its orientation. Panels (c) and (d) begin with a cue that indicates which information will be relevant. This is followed by the array of to-be-remembered items, along with distractors. After the inter-stimulus interval (ISI), the probe array appears with only cued information presented. In panel (c) the test-taker must indicate whether any box has changed colour. In panel (d) the test-taker must indicate whether the box with the white dot has changed orientation.

from the target array. Such manipulations introduce a filtering component to the task, increasing demands on top-down attention (Vogel, McCullough, & Machizawa, 2005). We refer to visual arrays with an attentional filtering component as *selective* visual arrays. In other visual arrays tasks no such instructions were given (Fig. 7.2a, b). Visual arrays without the filtering component were expected to mirror the complex span tasks in their relationships to primary memory, secondary memory, and Gf; we refer to them as *non-selective* visual arrays. Selective visual arrays were expected to show stronger relationships to attention control than their non-selective counterparts.

C7.P25   Shipstead et al. (2014) also derived latent factors representing attention control, primary memory, and secondary memory. Attention control was defined using anti-saccade accuracy, alongside the colour Stroop and arrow flanker interference effects. The primary memory latent factor was defined by accuracy in list recall below within the putative limits of primary memory capacity, and secondary memory capacity

was defined by list recall accuracy once this limit has been exceeded (see Tulving and Colotla, 1970).

C7.P26   Having described their measures, we can now outline some of Shipstead et al.'s (2014) major findings. In one analysis, primary memory, secondary memory, and attention control were used to predict correlated WMC and Gf factors. When inspecting the model (Fig. 7.3), the first thing to note is that the correlation between WMC and Gf is not significant after accounting for the influences of the predictors. That is to say, the relationship between WMC and Gf is entirely explained by their relationships with attention control, primary memory, and secondary memory. The second thing to note is that the only unique predictor of both Gf and WMC is secondary memory retrieval; neither primary memory or attention control uniquely predict both WMC and Gf once the intercorrelations of predictors is taken into account. However, this does *not* suggest that attention control and primary memory are unimportant in explaining the WMC–Gf association. Rather, the bulk of the shared variance between the WMC and Gf latent variables is actually accounted for by the indirect path through primary memory and attention control, seen in bold. Substantively, this suggests that attention control and primary memory *jointly* account for much of the shared variance between WMC and Gf. This is consistent with the notion that the use of attention to manipulate the contents of primary memory is a critical aspect of the WMC–Gf relationship, which
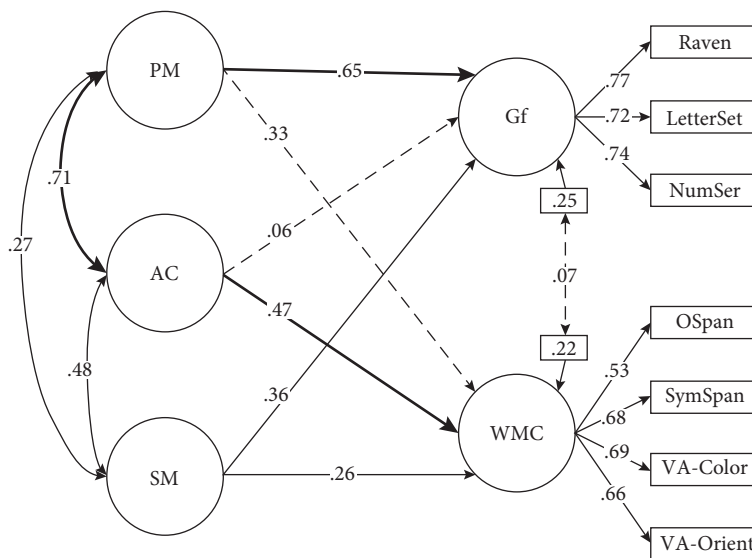
C7.F3   **Fig. 7.3** Primary memory (PM), secondary memory (SM), and attention control (AC) predicting WMC and Gf. WMC here is defined by two complex span tasks and the non-selective visual arrays tasks without the attentional filtering component. Broken paths are not statistically significant.

coincides with our thinking about the strong relationship between the running span (and related measures of WMC) and Gf.

C7.P27   This account of the relationship between WMC and Gf was further supported by models in which primary memory totally mediated the effect of attention control on Gf (Fig. 7.4a, b). Two such models were fitted, with WMC being defined either by complex and running spans (Fig. 7.4a) or by selective and non-selective visual arrays tasks (Fig. 7.4b). In Fig. 7.4a, variance unique to WMC as defined by two running spans was used to predict primary memory; all variance shared with complex span measures of WMC was used to predict attention control and secondary memory retrieval. In Fig. 7.4b, variance unique to the selective visual arrays tasks was used to predict attention control, while variance shared with non-selective visual arrays tasks was used to predict attention control and secondary memory retrieval. The substantive interpretation of both models is identical. Secondary memory retrieval once again predicted unique variance in Gf, as did primary memory. Crucially, attention control was not directly related to Gf, but exerted its entire effect indirectly through its influence on primary memory. One interpretation of these results is that attention control is related to WMC and Gf because it helps organize the contents of primary memory according to current goals. Given the strong relationship between tasks that require continual updating of primary memory and Gf, it is plausible that the ability to remove, inhibit, or otherwise disregard items in primary memory may be critical to performance on Gf tasks, whereas the ability to maintain items in memory may be more crucial to other kinds of working memory measures. Attention control would seem relevant in both cases (Shipstead et al., 2016).
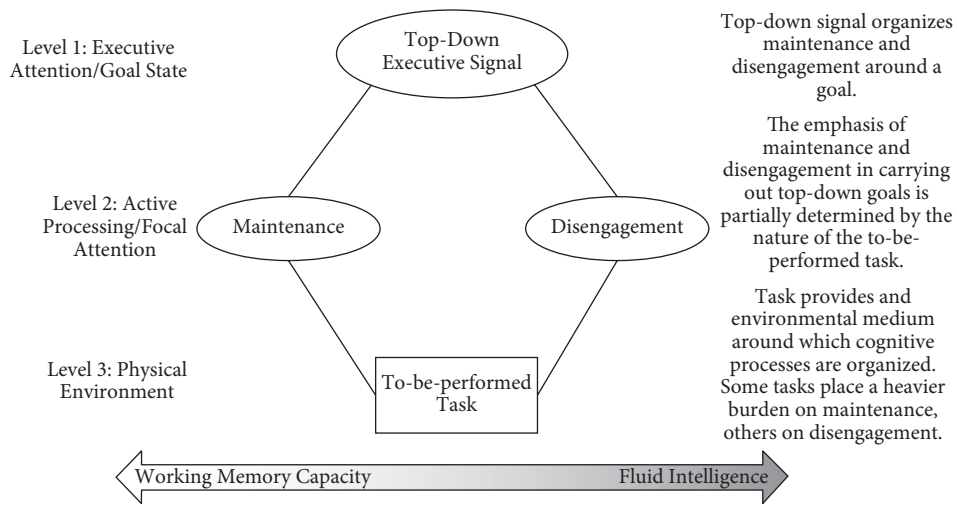
C7.P28   Before a more extensive treatment of our current framework, we would like to address a theoretical alternative that we think is increasingly untenable. In our view, WMC and Gf are correlated because they share common cognitive mechanisms. This account of the association between WMC and Gf runs counter to the more standard view that WMC contributes causally to Gf by maintaining representations that support the generation and testing of hypotheses (Chuderski, Taraday, Neçka, & Smoleń, 2012; Oberauer, Süß, Wilhem, & Sander, 2007; Shipstead et al., 2012). However, direct tests of predictions derived from this hypothetical causal relationship provide little evidence that maintenance of information in Gf tasks drives the WMC–Gf relationship (Domnick, Zimmer, Becker, & Spinath, 2018). For example, if WMC were a causal factor in performance on Gf tasks, one would expect performance on complex reasoning items to have stronger correlations with WMC measures than simpler reasoning problems, because more complex problems should have greater storage demands. This does not occur, however (Burgoyne, Hambrick, & Altmann, 2019; Unsworth & Engle, 2005). Further, much of the research attempting to improve intelligence via working memory training is predicated on the assumed causal link between memory storage and Gf (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi, Buschkuehl, Jonides, & Shah, 2011). These efforts have thus far proven futile (Redick et al., 2013), bolstering the position that WMC does not causally influence Gf. In the next section, we elaborate
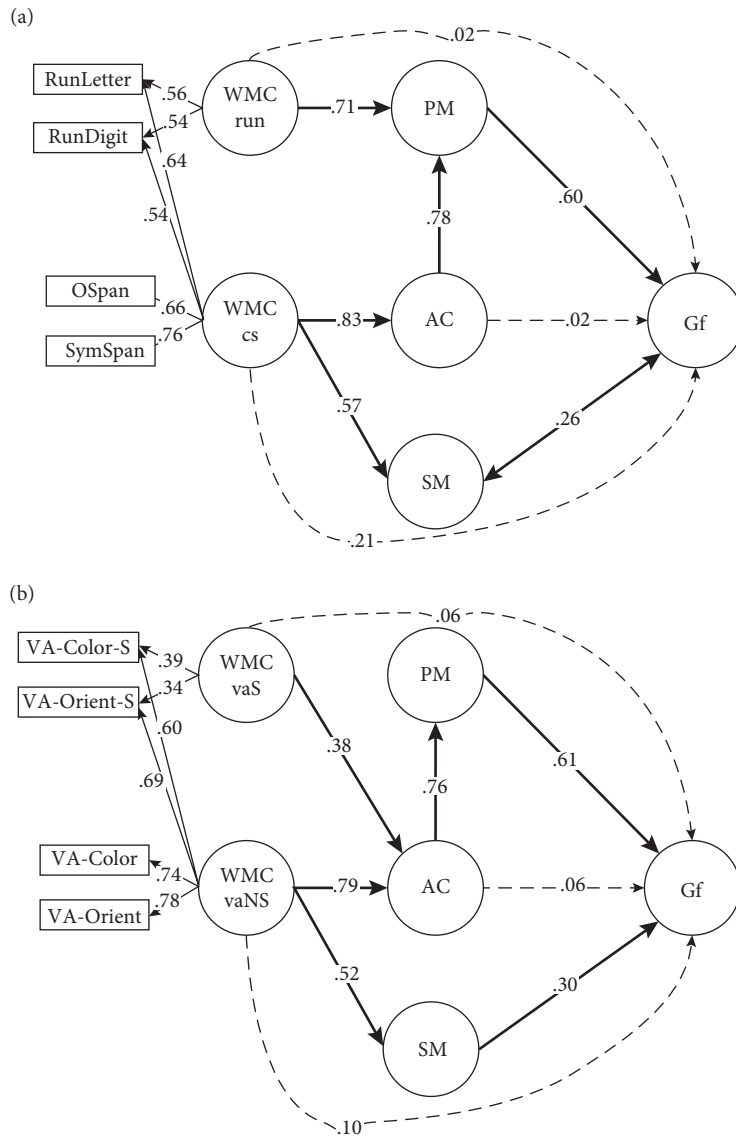
C7.F4 **Fig. 7.4** (a) Primary memory (PM), secondary memory (SM), and attention control (AC) mediating the relationship between span measures of WMC and Gf. WMrun is a working memory capacity factor defined by variance unique to running memory span tasks and WMcs is a working memory capacity factor defined by the variance common to running memory and complex span measures. (b) PM, SM, and AC mediating the relationship between visual arrays measures of WMC and Gf. WMvaS is a working memory capacity factor defined by selective visual arrays (i.e., those with an attentional filtering component) and WMvaNS is a working memory capacity factor defined by the variance shared by both non-selective and selective visual arrays. Broken paths are non-significant.

Source: Reproduced from Zach Shipstead, Dakota R.B. Lindsey, Robyn L. Marshall, and Randall W. Engle, 'The mechanisms of working memory capacity: Primary memory, secondary memory, and attention control', *Journal of Memory* and Language, 72, pp. 116–141, Figures 10 and 13, https://doi.org/10.1016/j.jml.2014.01.004 Copyright © 2014 Elsevier Inc. All rights reserved.

Level 1: Executive Attention/Goal State

Top-Down Executive Signal

Top-down signal organizes maintenance and disengagement around a goal.

Level 2: Active Processing/Focal Attention

Maintenance

Disengagement

The emphasis of maintenance and disengagement in carrying out top-down goals is partially determined by the nature of the to-be-performed task.

Level 3: Physical Environment

To-be-performed Task

Task provides and environmental medium around which cognitive processes are organized. Some tasks place a heavier burden on maintenance, others on disengagement.

Working Memory Capacity   Fluid Intelligence

C7.F5 **Fig. 7.5** The relationship between working memory capacity and fluid intelligence from the maintenance and disengagement perspective.

Source: Reproduced from Zach Shipstead, Tyler L. Harrison, Randall W. Engle, 'Working Memory Capacity and Fluid Intelligence: Maintenance and Disengagement', *Perspectives on Psychological Science*, 11, pp. 771–799. doi:10.1177/1745691616650647 Copyright © 2016, SAGE Publications.

this position and argue that WMC and Gf measures instead reflect different functions of attention.

Maintenance and Disengagement Theory

C7.S6

C7.P29   On the surface, WMC and Gf measures appear very different. WMC measures generally require participants to balance memory storage and processing demands, while Gf tasks have no explicit storage component and require participants to infer relations between the elements of a novel problem or puzzle to discover a solution. Yet, both abilities predict a broad assortment of behavioural outcomes and are highly correlated at the latent level. Given their seemingly divergent processing demands, what could account for the substantial overlap between measures of WMC and Gf? Recently, we have moved away from treating WMC and Gf as distinct cognitive processes. Instead, we regard them as patterns that emerge when common cognitive mechanisms are faced with the different constraints imposed by WMC and Gf tasks. This position is the starting point of maintenance and disengagement theory, a recently proposed generalization of the executive attention theory of WMC.

C7.P30   Fig. 7.5 depicts our current conception of the mechanisms underlying individual differences in WMC and Gf. Importantly, WMC and Gf themselves are not structural features of the model. Instead, we focus on the domain-general mechanisms that are constitutive of both. These are *maintenance* and *disengagement*, which, although distinct, are both executed by a top-down signal from a unitary executive attention

whenever controlled processing is required. Maintenance keeps representations in an active, accessible state in the face of distraction or interference. Conversely, disengagement expunges no-longer relevant representations, preventing them from affecting ongoing cognition (c.f. Bjork, 1970; Festini & Reuter-Lorenz, 2014). Failures of maintenance lead to the premature loss of still needed memory representations and to goal-neglect (e.g. attentional capture or mind-wandering), while failures of disengagement lead to a build-up of proactive interference and perseveration on outdated hypotheses or task sets. Individual differences in WMC arise when task demands place a greater emphasis on maintenance of information, though these tasks will also require disengagement of information to some degree (e.g. mitigating proactive interference). Individual differences in Gf arise when a task places a greater emphasis on disengagement from no-longer relevant information, though maintenance of task-goals and problem sets will be required. [5] Therefore, WMC and Gf arise from similar cognitive mechanisms but are reliant on these mechanisms to different degrees. Attention control is common to both.

C7.P31   When referring to maintenance and disengagement as mechanisms, we do not mean that they themselves are isolable processes. Rather, they should be viewed as categories of processes that broadly serve to maintain goal-relevant information or disengage from newly irrelevant information. For instance, disengagement may be carried out by cognitive inhibition, memory updating, tagging items in episodic memory to prevent retrieval, and so on. This broad-strokes approach is a major point of departure from similar sounding positions (e.g. the memory updating function in the unity/diversity model of executive functioning; Miyake et al., 2000; see also Bialystok, 2017).
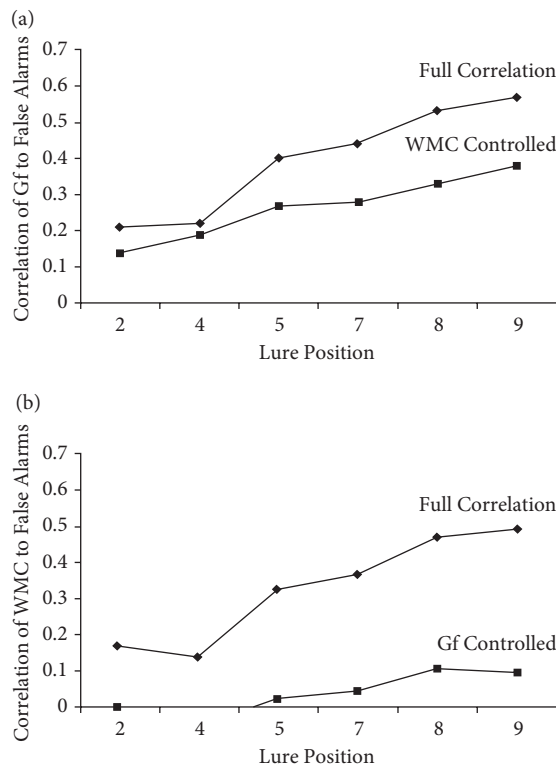
C7.P32   Beyond merely explaining the WMC–Gf relationship, maintenance and disengagement theory accounts for some curious findings not easily explained by its competitors. For instance, Shipstead and Engle (2013) showed that longer inter-trial intervals led to larger estimates of storage capacity on a non-selective visual arrays task. This suggests that visual arrays performance reflects more than mere capacity. Rather, scores also reflect the active removal of previously presented items to reduce proactive interference, with longer inter-trial intervals allowing more time for removal and interference reduction. Consistent with maintenance and disengagement theory, the correlation between WMC and visual arrays storage capacity did not change as a function of inter-trial interval. However, the correlation to Gf increased with longer intervals, suggesting that high-Gf individuals were actually able to take advantage of the extra time on long inter-trial intervals to *disengage* from the memory items presented in the previous trial. These results are difficult to explain with a strict maintenance perspective on the WMC–Gf relationship.[6]

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[5] One implication pointed out by a reviewer of this chapter is that while working memory training has had little success in improving performance on Gf tasks, interventions aimed specifically at improving disengagement skills may show more promise. This is untested, but would be a useful and important test of our theory and would provide tremendous applied benefits.

[6] This also conflicts with classic temporal distinctiveness accounts of forgetting, which would predict that mere time elapsed over the course of an inter-stimulus interval is sufficient to account for forgetting. If this were the whole story, it is unclear why higher Gf would be associated with more forgetting over the course of longer inter-stimulus intervals (e.g. Crowder, 1976).

C7.P33   Another piece of evidence comes from the *N*-back task (Shipstead et al., 2016). The three *N*-back task is a continuous memory task in which the participant is presented with one memory item at a time and must decide if that same item was presented three items back. A critical component to *N*-back tasks is the presence of lures, items that repeat in positions other than 3-back (e.g. 2-back). Once a lure is past 3-back it is no longer relevant and retaining it in memory will create interference as evidenced by false alarming to lure items. Lures are correctly rejected with greater frequency as lure position recedes. Fig. 7.6 plots the correlation between Gf and false alarm rates (Fig. 7.6a) and between WMC and false alarm rates (Fig. 7.6b). The raw correlations in each case follow a very similar pattern, but accounting for the influence of one ability on the other reveals a dissociation. Controlling on WMC diminishes the correlation between Gf and false alarming on the *N*-back somewhat, but there is still a discernible association. Controlling for the influence of Gf in the WMC–false alarming relationship virtually eliminates the correlation. Therefore, those higher in Gf, not WMC, are less likely to false alarm to a lure, an advantage that grows with the number of intervening

Fig. 7.6 (a) The correlation between fluid intelligence (Gf) and false alarm rates at different lure positions of the 3-back task. (b) The correlation between working memory capacity (WMC) and false alarm rates at different lure positions of the 3-back task.

C7.F6

items between the lure and target. The distance allows high-Gf individuals to disengage from the no longer relevant information. Low-Gf individuals are unable to similarly capitalize.

C7.P34   The very similar pattern observed with *N*-back performance for both WMC and Gf before imposing statistical control suggests an important lesson. Because WMC and Gf are so highly related, it is important to disentangle the two lest one misattribute an effect of WMC to Gf or vice versa. We have not always been so careful. For instance, Rosen and Engle (1997) used an extreme-groups design comparing high- and low-spans on a verbal fluency task and found that high-spans could name more exemplars of a category (e.g. types of animals) than could low-spans. Low-spans tended to re-retrieve previously generated exemplars, handicapping their performance by preventing them from retrieving new examples. High-spans did not suffer this difficulty as much, and retrieved many more exemplars as a result. Rosen and Engle concluded that WMC likely plays an important role in coordinating retrieval from long-term (i.e. secondary) memory. Shipstead et al. (2016) reached a different conclusion. Using a full range of ability and measures of both WMC and Gf, they showed that verbal fluency is uniquely predicted by Gf and not WMC, contra Rosen and Engle (1997). This is sensible in the maintenance and disengagement framework: high-Gf individuals are better able to disengage from already retrieved items, permitting the retrieval of new examples from long-term memory. WMC predicts verbal fluency only because of its correlation with Gf.

C7.P35   Beyond making sense of some otherwise unwieldy results, maintenance and disengagement theory also situates attention control within a broader research context. While maintenance supports the stability of our cognitive system, disengagement supports its flexibility by allowing the adoption of new patterns of thought and behaviour. The flexibility afforded by disengagement is theoretically more consistent with the way Gf has been defined and measured (i.e. the ability to reason about and solve novel problems) than a maintenance-based account of the WMC–Gf relationship. This distinction between stability and flexibility of cognition is also characteristic of other theories of cognition. For example, Smith (2003) differentiates two modes of thought: paradigmatic and revolutionary. Paradigmatic thinking is useful in routine problem-solving. Maintenance will allow for representations of routine rules to remain activated as one solves such problems (Harrison, Shipstead, & Engle, 2015). However, perseverating on routine rules when more creative or divergent thinking is required might impair reaching a correct solution. Smith (2003) referred to revolutionary thinking as being able to drop routine solutions and outdated hypotheses in favour of more creative 'out-of-the-box' thinking. We see clear parallels between this description of revolutionary and paradigmatic thought and the tenets of maintenance and disengagement theory. Thus, the theory has the potential to bridge the gap between seemingly disparate subject areas and hopefully will spawn new and fruitful investigations.

C7.P36   The maintenance and disengagement theory suggests that the reason WMC, Gf, and possibly other cognitive constructs are related to one another is due to their mutual reliance on attention control. One theoretical prediction derived from the theory,

therefore, is that attention control should mediate, largely or completely, the relationship between WMC and Gf latent variables. One problem for maintenance and disengagement theory (and the original formulation of the executive attention theory of WMC) is that tasks typically thought to measure attention control show little in the way of convergent validity, casting doubt on the existence of a unitary attention control ability (Karr et al., 2018; Rey-Mermet, Gade, & Oberauer, 2018). An alternative conclusion is that there are widespread measurement issues in studies of attention control, leading to difficulty in forming cohesive latent factors. Indeed, we regard many of the tools currently used in the literature as problematic for individual differences research (see Draheim, Mashburn, Martin, & Engle, 2019), raising questions about how best to measure attention control.

Measuring Attention Control

C7.S7

C7.P37 Theoretical work surrounding attention control has been stymied by widespread and historically acknowledged measurement issues associated with the correlational use of experimental tasks (Draheim et al., 2019). For example, few paradigms in psychology are as recognizable and robust at the group level as the colour Stroop task, which, again, requires a person to resist the automaticity of reading the name of a colour to report the colour in which the word is printed (Stroop, 1935). The Stroop interference effect is usually calculated by subtracting the mean reaction time on congruent trials (e.g. BLUE) from the mean reaction time on incongruent trials (e.g. BLUE). Since the trials differ in one and only one regard, the presence or absence of a mismatch between the word and typeface, subtracting one reaction time from the other should yield an estimate of how long it takes to resolve the conflict from competing responses on incongruent trials, a putative function of controlled attention (Norman & Shallice, 1986).

C7.P38 Many other tasks in the attention control literature are variations on this basic theme. Such tasks are premised on the subtraction methodology of Franciscus Donders (1868/ 1969). Although groundbreaking in assuming that mental events take a quantifiable amount of time and hence are open to empirical study, several of the method's base assumptions have been vehemently criticized (e.g. Sternberg, 1969). The method can only be applied under the assumption of a serial progression of information processing steps, so parallel processing is fatal to any straightforward interpretation of reaction time difference scores. Another prerequisite is the assumption of pure insertion, whereby one assumes that by adding a single element or alteration to a base task requiring multiple processing steps, they are only affecting processing in one stage and not others. This is a tenuous assumption at best and is likely often wrong.

C7.P39 While subtracting reaction times from similar tasks seems a simple and appealing method for isolating effects of interest, the assumptions bounding their interpretation mean that subtraction is probably inappropriate under many experimental circumstances. This is not to say that the use of the Stroop and other interference effects should be shunned by researchers outright. After all, the effects are robust and highly

replicable. It does, however, mean that interpreting such interference effects is murkier than researchers often presume, and interpreting them as pure indicators of the processes meant to be studied is often unjustified. These issues are well-known at the experimental level, but these effects are arguably more pernicious in individual differences and developmental research, and a host of other issues arise when these tasks are imported from the experimental domain to the differential (see Miller & Ulrich, 2013 for an excellent discussion of interpreting reaction time correlations).

C7.P40 Interpretive difficulties aside, subtractive effects pose a number of other problems for differential psychology. Experimental and differential psychology differ fundamentally in terms of the variance that they seek to explain (Cronbach, 1957). Experimental psychology seeks to understand how situational variables affect behaviour, whereas differential psychology seeks to explain factors that distinguish individuals from one another. These respective emphases lead experimental psychology to focus on within-participants variance (to the degree possible) and to strive to minimize between-participants variance. This is made explicit in the typical statistical methods employed in each tradition, with *t*-tests and ANOVAs comprising the brick-and-mortar of experimental psychology, while correlation, regression, and factor analysis, which rely on the very between-participants variance that experimentalists strive to minimize, inform much of differential psychology.

C7.P41 Despite this fundamental methodological and philosophical disconnect, much of our work can be seen as an attempt to achieve Cronbach's (1957) vision of a unified psychological science. We have been delighted to see others interested in bridging the gap between the two traditions, but doing so can be treacherous. The wholesale import of experimental tasks into differential research contexts presents one pervasive misstep. The impulse is laudable given the success of tasks like the Stroop task at the experimental level. However, they tend to be fairly low in between-participants variability (Hedge, Powell, & Sumner, 2018; Rouder & Haaf, 2019), which is a prerequisite for observing strong correlations, including estimates of reliability.[7] A major reason for this lack of between-participants variance is the subtraction methodology employed in calculating dependent variables in many experimental tasks. Difference scores and measures relying upon them have been criticized by psychometricians for their unreliability (Cronbach & Furby, 1970; Edwards, 2001; Paap & Sawi, 2016), which is a by-product of the correlation of their components (Chiou & Spreng, 1996). The components of an attention control task (e.g. congruent and incongruent Stroop trials) tend to be quite reliable themselves, but much of their reliable variance is subsumed by their correlation. This produces difference scores that are much less reliable than their components almost by mathematical necessity (but see Trafimow, 2015). Removing the common reliable variance also increases the proportion of error variance reflected in the score, often leading to small correlations, low reliability, and difficulty demonstrating validity

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[7] Ironically, this homogeneity is a reason the tasks perform so well experimentally, given the logic of statistical tests.

(Hedge et al., 2018) which, in turn, often leads researchers to accept the null hypothesis that there is no correlation between variables.

C7.P42   Another reason to be wary of reaction time difference scores in particular is the possibility of speed/accuracy trade-offs. In many cases, speed and accuracy of responding exist in opposition, and individuals vary in their prioritizing one over the other (Heitz, 2014). For instance, cognitive ageing researchers often contend with older adults' strong bias to favour accuracy over speed of responding (Starns & Ratcliff, 2010), and those higher in cognitive ability may slow down after committing an error to avoid future errors, while lower-ability participants show no slowing in subsequent trials (Draheim, Hicks, & Engle, 2016). Differing speed/accuracy emphases can lead to spurious conclusions if not accounted for, making straightforward interpretation of correlations impossible. Given that many of the effects typically of interest in experimental attention control tasks are purely reaction-time based and do not account for one-half of the speed/accuracy dynamic, possible differences in speed/accuracy interactions are a major reason to avoid them in differential research.[8]

C7.P43   These measurement deficiencies are one possible reason for the widespread difficulty in forming balanced attention control factors (often operationalized using 'inhibition' tasks). This difficulty has been suggested as evidence against the existence of a unitary attentional control ability: if 'attention control' measures truly tap the same underlying construct, there should be greater cohesion in terms of task intercorrelations and factor loadings. Failure to consistently find such relationships could indicate that control processes are not unitary, and that task-specific control processes lie at the root of successful performance (Rey-Mermet et al., 2018).

C7.P44   This interpretation is potentially viable, but dubious given the psychometric difficulties associated with reaction time difference score measures (and difference scores more broadly). Moreover, attempts to rectify these measurement issues have yielded conflicting results. For example, a recent study by Rey-Mermet, Gade, Souza, von Bastian, and Oberauer (2019) attempted to minimize the influence of speed/accuracy trade-offs in an array of attention control tasks. They did so by instituting a response deadline that they reasoned should penalize both extremely slow accurate responding and fast error-prone responding equally. The deadline was based on speed of responding on a series of neutral trials in which attentional processes would not be expected to operate (e.g. pro-saccade trials in an anti-saccade task). The procedure was also expected to limit the influence of processing speed, which has been proposed as a possible basis of the relationship between WMC and Gf (e.g. Fry & Hale, 1996). They also took steps to minimize the influence of associative learning, episodic memory, and stimulus carryover effects. They were unable to form a coherent latent factor from the attention control measures, and individual tasks showed little relationship to WMC or

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[8] While pure reaction time tasks are problematic in this regard, this can be less of a concern for accuracy-based tasks (see Draheim et al., 2019; Wickelgren, 1977). However, accuracy-based difference scores are also vulnerable to psychometric issues and interpretive difficulties.

Gf. They interpreted this as indicating a widespread conflation between general processing speed and attention control.

C7.P45   One possible reason for their null findings is their decision to use accuracy difference scores as dependent variables for their tasks. They did so in order to eliminate the possibility that different types of dependent variables might contribute to underwhelming relationships between traditionally reaction-time based executive functioning measures and accuracy-based measures of WMC and Gf. Accuracy-based difference scores suffer the same reliability concerns and are also difficult to interpret unless one is willing to assume the strictures of the subtraction methodology. Even so, we would be remiss not to note that the pattern of results for their anti-saccade task did not change when only accuracy on anti-saccade trials was used, and the reliability of their measures was uniformly very high for difference scores. This is an interesting departure from the preponderance of psychometric theory and empirical investigations of difference score reliability, although there are circumstances under which difference scores obtain acceptable reliabilities (Trafimow, 2015). Even so, there are several reasons to be cautious about their results. Their use of a thresholding procedure to account for processing speed and speed/accuracy trade-offs is novel and requires validation, especially in light of numerous macro-analytic studies which find that processing speed is unable to account for the relationships between executive control and other cognitive constructs (Cepeda, Blackwell, & Munakata, 2013; McCabe et al., 2010) or between WMC and Gf (Colom et al., 2008; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Redick, Unsworth, Kelly, & Engle, 2012). We consider more evidence that processing speed may be a suboptimal explanation in our 'Alternative Views' section.

C7.P46   Draheim, Tsukahara, Martin, Mashburn, and Engle (2020) took a different approach. They tested a battery of classic, modified, and novel attention control tasks. These included standard and modified versions of the colour Stroop and arrow flanker tasks. Rather than relying on reaction time difference scores as a dependent variable, the modified versions of the tasks followed a thresholding procedure whereby a stimulus presentation rate or a response deadline was adjusted based on block-by-block response accuracy. There were also several other tasks which relied solely on accuracy as a dependent variable. These included an anti-saccade, a selective visual arrays task, and a novel task modelled on a perceptual vigilance task and the anti-saccade. These modified accuracy-based attention tasks showed stronger intercorrelations, were more reliable, and showed stronger relationships to both WMC and Gf than the reaction-time difference score measures. In fact, when defined by some of the strongest performing measures, the attention control latent factor totally mediated the relationship between WMC and Gf, consistent with predictions derived from maintenance and disengagement theory. Furthermore, these relationships were still significant even after accounting for the influence of a latent variable defined by processing speed measures. Draheim et al. (2020) took this pattern as confirmatory evidence for a unitary domain-general attention control ability.

C7.P47   One potential objection to the interpretation of Draheim et al. (2020) is that their so-called attention control latent factors could contain variance not associated with

attention control. As their measures were not subtractive, the latent factors derived from them could contain common but process-irrelevant variance, such as that reflecting processing speed or short-term memory storage. This criticism presumes that difference scores are the only way to achieve something close to process-purity and follows from the logic of the subtraction methodology. If the strictures of the subtraction methodology are met, the criticism is approximately correct.[9] However, we have argued the subtraction methodology's assumptions are often invalid, creating difference scores that are difficult to interpret. A better means of achieving our measurement goals is to adopt latent variable methodologies and to measure constructs via broad factors comprised of structurally dissimilar tasks, which Draheim et al. attempted. The broader concern is well-taken, however. This was an overtly exploratory study and, although the results were promising, more work is required to validate the tasks before we can confidently attest to the processes they measure.

C7.S8

Alternative Views

C7.P48 Over the course of our writings, we have at various times drawn comparisons between our own work and other prominent theories of working memory and WMC. In particular, we have been sympathetic to the basic tenets of Cowan's (1988, 1999) embedded process model and Oberauer's concentric theory of WMC (Oberauer, 2002; Oberauer et al., 2007). These views share a basic scaffolding in that they assume that short-term (primary) memory consists of activated units of long-term memory. They differ in the role of attention. The embedded process model allows for about four chunks of information to be held active within the focus of attention, where they are safeguarded from the build-up of proactive interference and time-based decay (Cowan, 2001; Cowan et al., 2005). The concentric model, meanwhile, permits a single chunk to inhabit the focus of attention without proactive interference or decay, but other pieces of information can be held active outside the focus of attention by building, breaking, and updating arbitrary bindings between the item within the focus of attention and other items in secondary memory. Currently bound items are equated with primary or short-term memory. At this time, we favour the concentric model, partly based on recent data suggesting that interference occurs well within the capacity of focal attention assumed by the embedded process model (Allen, Baddeley, & Hitch, 2014; Shipstead & Engle, 2013). However, our views diverge from the concentric model in several important ways. For one, the model assumes that binding and unbinding are separable from attention processes (Wilhelm et al., 2013). In our view, binding and unbinding would putatively be classified as maintenance and disengagement processes, respectively, and would hence be regulated by attentional resources. Consistent with our characterization, binding has been shown to be disrupted by attention load (Allen et al., 2014).

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[9] Approximately because the difference score would be a fairly pure measure (assuming highly reliable components), but we would still regard latent variable analysis as a viable and more general alternative (Donaldson, 1983).

C7.P49   Our theoretical framework is sufficiently general that we find relevant similarities with several theories of working memory, certainly more than we have space to discuss here. We would like to close by addressing a position that we find less amenable and that we touched upon previously: that the relationship is actually due to individual differences in processing speed.

C7.S9   Processing Speed

C7.P50   As previously noted, processing speed has been proposed as a primitive and an explanatory alternative to attention control. We and others have been addressing this criticism in various forms for years (Conway et al., 2002; Heitz & Engle, 2007; Stankov & Roberts, 1997; Unsworth et al., 2004). We believe that the popularity and persistence of processing speed as an explanatory device warrants a somewhat protracted analysis. Processing speed has been shown to relate to both WMC and Gf (although less consistently with WMC; Conway et al., 2002; Fry & Hale, 1996; Kranzler & Jensen, 1989; Redick et al., 2012). Given difficulties in deriving strong, stable latent factors using well-known attention control measures, processing speed seems a reasonable avenue for exploration. However, there are good theoretical and empirical reasons to be sceptical.

C7.P51   One is the sheer under-specification of what is meant by processing speed: speed of *what*, exactly? This question often goes unaddressed by researchers using processing speed to explain individual differences in higher cognition. Presumably, what is meant is a global speed difference whereby people differ similarly in the speed of all information processing, perhaps due to underlying differences in neurophysiological efficiency (Jensen, 1998; Reed & Jensen, 1992). We refer to these as global speed differences. An alternate interpretation would be that whatever processing mechanisms are involved in a given task, they operate more quickly for some people than others, but there are intra-individual speed differences across different processes. We call these local speed differences. Evidence for global processing speed differences is somewhat shakier than is immediately apparent, however. Rabbitt (1996) has argued that, even when the proportion of the speed difference between two or more individuals is variable across tasks (suggesting local speed differences), plotting these ratios can still produce strong, positive linear trends implying global speed differences. This risks masking local speed differences by erroneously creating the impression of uniform differences in a global processing speed.

C7.P52   Where local process-specific speed differences emerge, it surely makes more sense to deemphasize differences in speed rather than to treat them as central to theories of cognition. That is to say, if the speed of *what* matters, then it surely makes more sense to treat 'speed of processing' as a cognitive outcome rather than a causal primitive. Otherwise, one is simply capitalizing on the trivial fact that cognition unfolds over time. Rabbitt (1996) makes a similar point. Noting that speed is the only possible metric in many processing speed tasks, he writes '[to] deduce … that individual differences in speed (which are all we can measure) must therefore necessarily be the functional

bases [sic] of individual differences in ability is to weekly succumb to tautology' (p. 85). Reliable differences in the speed with which people enact mental processes emerge and relate to cognitive ability, but this fact alone is no justification for using speed as an explanatory primitive.

C7.P53   Jensen (1998) offers a fascinating response to the 'speed of what' question. He notes that, 'The speed of *controlled processing* and the capacity of working memory are of great importance because of their heavy contribution to variance in [general intelligence]' (p. 248, emphasis added). He asserts that many hallmark measures of processing speed work by essentially forcing controlled processing, a position that has received some empirical support (Wu et al., 2018). Thus, while some suggest executive control tasks are confounded with processing speed (e.g. Rey-Mermet et al., 2019), we submit that an alternate hypothesis, that 'processing speed' tasks may include variance better construed as reflecting attention control, is both tenable and likely.

C7.P54   Evidence for this position comes from a few different areas. One is the 'worst performance rule', the observation that the slowest responses on a reaction time task exhibit the strongest (negative) relationship with cognitive ability (Coyle, 2003; Schubert, 2019). One explanation for this is that the slowest responses are most diagnostic of attention capture; losing focus yields slower responses and those with better attention control abilities lose focus less often. This interpretation has been borne out by changes in response time distributions as a function of practice. As people become more skilled in a task, their mean reaction time decreases. The main driver of this decrease is not a shifting of the entire response time distribution, but rather fewer severely delayed responses (Rabbitt, 1996). This is precisely what one would expect if the slowest responses index controlled attentional processes. As the task becomes automatized, attention control is required less for responding, resulting in less positively-skewed reaction time distributions. This would imply that one reason processing speed predicts cognitive abilities is that attention control helps determine the shape of the reaction time distribution.

C7.P55   Another reason to suspect an executive control contribution to processing speed comes from studies indicating that more complex processing speed measures exhibit stronger relationships with cognitive ability (Ackerman, Beier, & Boyle, 2002; Cepeda et al., 2013). As complexity increases, it becomes more likely that attention control will be required for goal maintenance and manipulation of memory representations for successful task performance. This pattern has been shown to be modulated by age, with both young children and older adults exhibiting greater reliance on executive control in simpler speed tasks than do young adults (Cepeda et al., 2013), a finding consistent with proposed developmental trajectories of cognitive control (Cappell, Gmiendl, & Reuter-Lorenz, 2009; Craik & Bialystok, 2006; Jones, Rothbart, & Posner, 2003; Li, Hämmerer, Müller, Hommel, & Lindernberger, 2009). Importantly, this suggests that the relationship between processing speed and developmental change in WMC and Gf ascribed to processing speed may be, at least partly, a misattribution (Fry & Hale, 1996; Salthouse & Babcock, 1991).

C7.P56   Although we are sceptical of processing speed's ability to account for the covariation of WMC and Gf in any sort of theoretically interesting way, this remains an empirical question. One barrier to answering it is the sheer number of tasks that are purported to measure processing speed and the differences in their structure, demands, and implementation (see Schubert, 2019). We believe that the field would benefit from more concentrated, principled efforts to securely establish the construct validity of both processing speed and attention control (Cepeda et al., 2013).

Conclusion

C7.S10

C7.P57   The executive attention theory of WMC initially postulated that the ability to maintain goal-relevant items in memory by way of attention resources was central to many cognitive abilities and real-world outcomes and was perhaps the thread connecting all sorts of controlled cognition. We have since expanded our focus. This initial articulation of the importance of WMC is not wrong, but rather incomplete. It ignores that any goal-relevant information held active in memory will inevitably become irrelevant at some future time and prove disruptive if not removed, suppressed, blocked, or inhibited. These respective functions, maintaining and disengaging from items in memory, are uniquely indexed by measures of WMC and Gf, respectively. Executive attention coordinates maintenance and disengagement processes. The original conjecture that WMC comprises the core of individual differences in controlled cognition is more aptly rephrased by saying that the ability to dynamically and flexibly control attention is at the core of controlled cognition.

C7.P58   This perspective is still novel and much of the preceding is admittedly speculative (although see Martin et al., 2020 for a recent application of the theory to language ability), but the maintenance and disengagement framework has several virtues. For one, it decentres maintenance processes, encouraging a more active and dynamic view of the cognitive system. It also has the potential to organize much of the literature surrounding the relative predictive utilities of WMC and Gf while providing a general rubric for gauging the likelihood that previous work erroneously attributes an effect of Gf to WMC or an effect of WMC to Gf. Finally, it places the often ignored distinction between cognitive processes and the tasks used to measure them in the theoretical foreground.

C7.P59   The novelty of the maintenance and disengagement framework, coupled with extant criticisms of our work, suggests several lines of future investigation. Of immediate concern is the continued development and validation of psychometrically sound measures of attention control. The previously discussed anti-saccade task is a prime example of this, but, as we and others note, a single task is an insufficient basis for a theory of cognition (Draheim et al., 2019; Draheim et al., 2020; Rey-Mermet et al., 2018). Relatedly, more direct investigations of both attention control and processing speed, specifically aimed at construct validation, are clearly in order.

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