Perspectives on Psychological Science
2016, Vol. 11(1) 74–100

DOI: 10.1177/1745691615596790
pps.sagepub.com

A Working Memory System With Distributed Executive Control

André Vandierendonck
Department of Experimental Psychology, Ghent University

Abstract
Working memory consists of domain-specific storage facilities and domain-general executive control processes. In some working memory theories, these control processes are accounted for via a homunculus, the central executive. In the present article, the author defends a mechanistic view of executive control by adopting the position that executive control is situated in the context of goal-directed behavior to maintain and protect the goal and to select an action to attain the goal. On the basis of findings in task switching and dual tasking, he proposes an adapted multicomponent working memory model in which the central executive is replaced by three interacting components: an executive memory that maintains the task set, a collection of acquired procedural rules, and an engine that executes the procedural rules that match the ensemble of working memory contents. The strongest among the rules that match the ensemble of working memory contents is applied, resulting in changes of the working memory contents or in motor actions. According to this model, goals are attained when the route to the goals is known or can be searched when the route is unknown (problem solving). Empirical evidence for this proposal and new predictions are discussed.

Keywords
working memory, executive control, executive function, task switching

Many daily activities such as reading, writing, making a shopping list, carrying on phone conversations, deciding where to go on holidays, and many more require working memory. For example, when reading a text, meanings expressed in the parts of a sentence are kept in memory until they can be integrated in an overall meaning at the end of the sentence. Besides memory storage capacity, this task involves executive control to divide attention over sentence processing and memory maintenance of the sentence part. The term *working memory* has been coined to refer to such combined usage of memory and executive control to support an activity or a skill. Language production and comprehension (e.g., Just & Carpenter, 1992), mental arithmetic (e.g., DeStefano & LeFevre, 2004), reasoning (e.g., Klauer, Stegmaier, & Meiser, 1997), attentional control (Kane, Bleckley, Conway, & Engle, 2001), and many other tasks require working memory (WM) support to represent a situation, to keep track of progress, and to maintain interim results. In affective and emotional processing (e.g., Eysenck & Calvo, 1992), especially in states of depression and anxiety, people entertain worrying thoughts and engage in rumination but also try to counteract or suppress such thoughts, thus occupying memory and executive control that otherwise would be available for other activities. The degree to which such rumination consumes WM resources varies across persons because the amount of WM capacity (i.e., the ability to maintain information while performing a demanding task) differs across individuals and shows a robust and important relation to fluid intelligence (e.g., Engle, Tuholski, Laughlin, & Conway, 1999). WM capacity is predictive of a range of skills, including reading comprehension (e.g., Unsworth & McMillan, 2013) and numerical skills (Rotzer et al., 2009). WM also is considered to play a major part in the development of mental capacity (Case, Kurland, & Goldberg, 1982), and it is an important factor in psychopathology, particularly in autism and attention-deficit/hyperactivity disorder (e.g., Pennington & Ozonoff, 1996) but also in schizophrenia and dementia (e.g., Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986).

Corresponding Author:
André Vandierendonck, Department of Experimental Psychology, Ghent University, Henri Dunantlaan 2, B-9000 Gent, Belgium
E-mail: Andre.Vandierendonck@UGent.be

After four decades of WM research, most present-day WM theorists still rely on a homunculus to account for the executive or attentional control that is considered to be one of the core WM functions. This homunculus is called central executive (e.g., Baddeley, 1986, 2000; Baddeley & Hitch, 1974; Cowan, 1999, 2005), central attention (e.g., Barrouillet, Bernardin, & Camos, 2004), or executive attention (e.g., Engle, Tuholski, et al., 1999). Not only in WM but also in action control and behavior change, control processes are attributed to a homunculus; however, understanding of how such control is performed has not increased. For that reason, some researchers have argued that all these homunculi must be banished from theories (Verbruggen, McLaren, & Chambers, 2014). In the present article, I pursue this argument by presenting and elaborating a theoretical model that accounts for executive control processes in WM without the help of a homunculus.

The reason that the theoretical conception of WM includes executive control (or whatever one chooses to call it) originates from the assumption that WM uses short-term memory resources to support other cognitive activities, such as mental arithmetic, language, reasoning, and problem solving. All these activities need memory resources to attain their goal. Because these resources have to be shared between these activities and memory itself, the assignment of the resources typically occurs under intentional control. Such an intentional or goal-directed perspective requires proper control mechanisms to facilitate goal attainment. Thus, WM not only provides domain-specific memory resources to temporarily maintain information but also domain-general mechanisms to support these goal-directed cognitive activities. For example, in performing mental arithmetic, the WM system not only provides verbal WM storage to maintain interim results but also provides storage to maintain the task goal and the selected method(s) to attain this goal (Hitch, 1978; Imbo, Vandierendonck, & De Rammelaere, 2007).

In the model I describe in this article, the multicomponent WM model of Baddeley and Hitch is used as a starting point and as a reference (Baddeley, 2000; Baddeley, Allen, & Hitch, 2010; Baddeley & Hitch, 1974). Several reasons motivate this choice. First, although it is the oldest model around,[1] the multicomponent model still plays a leading role in present-day WM research. Second, this model has inspired a large share of the research on WM. Finally, because of the diversity of the WM models defined in the literature, it is not possible within the scope of one article to formulate an account that fits all models, even though the general ideas presented here are assumed to be valid in the context of other WM models that rely on a homunculus to account for controlled processes.

As the name suggests, the multicomponent WM model consists of a collection of components or modules that together constitute the WM system. At the top of the system, the *central executive* component is assumed to incorporate the control function. It oversees the operation of the domain-specific components of the WM system: the *phonological loop*, which maintains phonologically coded verbal information for short periods of time (Baddeley, 1986; Baddeley, Lewis, & Vallar, 1984); the *visuospatial sketch pad*, which stores visual and spatial information (Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Logie, 1995); and the *episodic buffer*, which binds the contents of the modality-specific systems to episodic long-term memory (Baddeley, 2000). The central executive also supervises controlled and goal-directed processes, including reasoning and problem solving. This conceptualization of executive control has been defended as representing an intermediate step toward a better understanding of the WM system. Unfortunately, over time, phenomena that could not be immediately understood by the operation of the domain-specific modules have been accounted for by the operation of the ill-understood central executive.

Later on, Baddeley (1996a, 1996b) argued for a fractionation of the central executive into simpler components, which finally resulted in the addition of the episodic buffer as another component in the multicomponent model (Baddeley, 2000). The proposed function of the episodic buffer consisted of binding features to form a temporarily united representation (as in connecting a specific color to a specific form or an action to an actor in sentence processing). There is no doubt that the inclusion of the episodic buffer improved the scope of the model. Nevertheless, it did not result in a reduction of the power of the central executive because further research has shown that the hypothesized binding operations attributed to the episodic buffer do not involve executive control (Allen, Baddeley, & Hitch, 2006; Allen, Hitch, Mate, & Baddeley, 2012; Baddeley et al., 2010; Baddeley, Hitch, & Allen, 2009). In another effort to fractionate the central executive, Miyake et al. (2000) proposed replacing it with specific executive functions, such as changing focus from one intention to another (set shifting); adapting the contents of WM by adding, replacing, or deleting contents (memory updating); and suppressing or decreasing the degree of activation of WM contents (inhibition). Although Miyake et al. took an important step forward by rooting these executive functions in measured variables, their attempt failed to account for dual-task performance. In still another attempt, Vandierendonck, Szmalec, Deschuyteneer, and Depoorter (2007) tried to redefine the central executive by specifying the basic processes underlying executive control. Thus far, these efforts have failed to replace the central executive with an account that does not involve a homunculus and that is more defensible scientifically via attribution of executive control to the operation of simpler processes.

In this article, I present an adaptation of the multicomponent WM model in which the central executive is deleted from the WM architecture and replaced by a dedicated WM component that maintains the conditions and constraints of the currently scheduled intentional action and relocates the control actions to the application of specific rules that are automatically triggered when they match the conditions and constraints represented in the WM stores. The latter part is achieved in a so-called production system, without a need for an autonomous controlling agent or homunculus. The proposed changes are substantiated in reference to published empirical findings. For this reason, I first review the empirical findings that help to constrain the WM architecture. Next, I elaborate the implications of these findings for the conceptualization of WM. Finally, I explain how conditions represented in WM can automatically trigger rules that result in intentionally controlled behavior.

Empirical Constraints on the WM Architecture

WM provides domain-specific as well as domain-general resources: On one hand, it provides temporary storage for tasks that require maintenance of information for a brief period of time; on the other hand, it supports control of intentional action. For example, in the execution of a simple cognitive task such as judging whether a digit is odd or even (parity task), not only are a temporary representation of the digit and its activated associations (e.g., "even") needed for the duration of task execution, but also storage must be made available for the representation of the goal and the way to achieve it (task set). However, a mechanism that drives the control processes (the realm of the central executive) also is needed because temporary activations or representations of the goal and the way to achieve it do not control other processes, as they are merely temporary memory contents. Before elaborating these storage and control mechanisms in more detail, I summarize knowledge about controlled processes and the role of WM in such processing, first briefly presenting some relevant findings from task-switching research and then discussing some relevant findings from dual-task research.

Constraints from task switching

Switching between tasks occurs on several occasions each day. While you are reading a text, a phone call may remind you of a promise; you note down a reminder on a post-it and return to reading, trying to figure out where you left off. Switching is not always experienced as a demanding event. However, research on task switching has shown that a task switch almost always comes with a cost expressed as a slower and more error-prone response than a situation in which no switching is required. According to the present state of task-switching research (cf. Kiesel et al., 2010; Logan & Gordon, 2001; Monsell, 1996, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010), a successful task switch depends on the outcome of a competition between processes related to the present intention and processes that are driven by carryover from activities related to the previous, no-longer-relevant intention (e.g., task-set inertia; Allport, Styles, & Hsieh, 1994).

Task-control processes. Several kinds of processes are involved in this competition. To clarify these processes, let us take as an example switching from the execution of a magnitude judgment task (deciding whether a digit is smaller than or larger than 5) to a parity judgment task (deciding whether a digit is odd or even). The parity task requires the categorization of a digit as odd or even; in the magnitude task, the same digit must be categorized as small (smaller than 5) or large. In other words, the correct response to the digit depends on the task. In this particular case, one of two keys must be pressed. For the parity task, the instruction is to respond with a left key press when the digit is odd and with a right key press when it is even. Similarly, the magnitude task requires a left response for a small digit and a right key press for a large digit. Each trial starts with a cue that indicates which task must be performed. The cue is followed by the presentation of a digit.

Using this pair of tasks, Figure 1 illustrates how the execution of the parity judgment task may be affected by previous executions of a magnitude judgment task. The figure shows four pathways that are involved in the competition between goal-directed (Pathway 1) and interference-based (Pathways 3–4) processing. The cue initiates goal-directed processing. Via a learned association, the cue points to a task goal that after activation results in the configuration of the task set (Pathway 1), which is an ensemble of task-execution parameters (Logan & Gordon, 2001). For the tasks in the example, the task set includes settings of the orientation of attention (attention focused on a point in space where the digit will appear), stimulus categorization rules (categories odd and even for the parity task; small and large for the magnitude task), response mappings (e.g., press left key for odd), stimulus modality (visual or aural presentation of digits), response modality (manual or vocal response), and speed-accuracy tradeoff (stress on accuracy, stress on speed, or equal stress on both).

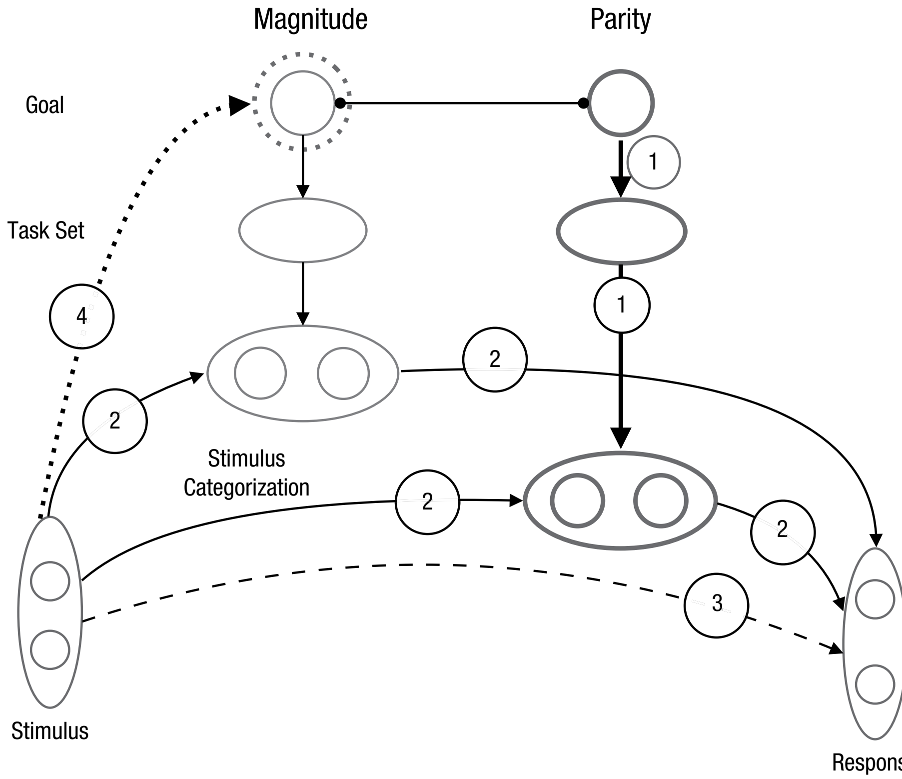

Fig. 1. Schematic description of the stages involved in goal-directed processing. In the top-down pathway (1), first a goal is selected (parity: odd/even judgment). This leads to configuration of the corresponding task set and biasing of the stimulus categorization towards the odd-even judgment rules. In the bottom-up pathway (2), the stimulus is linked with both the magnitude (small/large) and the parity categorization (in bold). Due to top-down biasing, the correct stimulus categorization is selected, which leads to a correct response. In previous episodes, a stimulus-response association (3) may have been learned; this association automatically triggers the previously associated response. If this response is incorrect, the conflict between the incorrect and the correct responses must be resolved. It is also possible that in previous episodes, a stimulus-task association has been formed, for example, with the magnitude task (4). This leads to a goal conflict, which propagates all the way down via task set and stimulus categorization to response.

Activation of the goal and configuration of the task set take some time, after which the conditions are set for activation of processes that result in goal achievement (Logan, 2003; Meiran, 1996, 2000; Monsell & Mizon, 2006; Rogers & Monsell, 1995). These processes include activation of the target categorization (e.g., odd), activation of the category-response mapping (if odd, press left), and finally activation of the motor response (left key press). Some of these processes are so well practiced that they also occur via direct target associations (Pathway 2). Such direct association may activate an irrelevant categorization, which in turn may activate its associated response, thus creating a competition with the task-relevant chain of events.

Repetitions of stimuli or stimulus features prime repetition of the associated response (Pashler & Baylis, 1991a, 1991b). The direct stimulus-response (S-R) association (Pathway 3) can bypass the goal-directed pathway (1) to the response. Task repetition enhances performance efficiency, but when the task changes, application of the S-R association may result in an error. Controlled processing is needed for the goal-directed processing pathway to be favored over the direct S-R link (Schuch & Koch, 2003; Verbruggen, Liefooghe, & Vandierendonck, 2006).

Research has also shown that the target stimulus can become associated with the task (Waszak, Hommel, & Allport, 2003), resulting in the creation of a stimulus-task association (Pathway 4). When a particular target is uniquely linked to one of the tasks (e.g., when the digit 2 would only occur in the context of the parity task), a direct stimulus-task association (2-parity) bypasses effortful goal-directed processing and results in faster goal achievement without risk of errors. However, when occasionally the target occurs in the context of the other task (e.g., the digit 2 unexpectedly occurs in the context of the magnitude task), goal achievement of the magnitude task may completely fail. The occurrence of such a bypass is difficult to control because the stimulus-task association directly activates the task goal. If this activation is fast, the incorrect task goal may be the first one becoming active so that it can easily win the competition from the correct goal. If on the contrary, activation of the correct goal occurs first, it is more likely to win the competition.

This brief sketch summarizes the task-processing stages at which biases and processing conflicts may occur. At each of these stages, cognitive control operations resolve the conflicts to achieve the relevant task goal. More detailed information can be found in the literature on task-switching and dual-tasking performance (J. W. Brown, Reynolds, & Braver, 2007; Gilbert & Shallice, 2002; Kiesel et al., 2010; Logan & Gordon, 2001; Monsell, 2003; Vandierendonck et al., 2010; Waszak et al., 2003).

Interaction with WM. Notwithstanding the huge number of articles published on task switching in the last two decades, the number of studies of the relationship between task switching and WM is rather modest (Kiesel et al., 2010; Vandierendonck et al., 2010) and addresses only three research questions, namely, the role of verbalization in task switching, the trade-off of WM and task-switching efficiency, and the role of WM in voluntary task choice. Because of their relevance to the present concern (i.e., how task-switching processes constrain the WM architecture), I consider each of these three lines of research in some detail.

Inner speech and verbalization. By far, the largest number of studies have been devoted to the first of these three research questions: the role of *verbalization* and *inner speech* in task switching. Goschke (2000) used letter and color categorization tasks and reported smaller switch costs when the task name ("letter" or "color") was verbalized before each stimulus (a colored letter) than when a verbal distractor ("Monday" or "Tuesday") was named. This finding is consistent with the hypothesis that task-set reconfiguration includes intention retrieval.

In a seminal study, Baddeley, Chincotta, and Adlam (2001) investigated how a verbal memory load affects task-switching performance. Participants applied simple arithmetic operations (+1, −1) to lists of digits (1–9) in either single-task (only addition or subtraction) or alternating-task (+1, −1, +1, −1, . . .) lists, with or without task cues (plus or minus signs). Confirming the typical switch cost, responses were slower on alternating-task lists than on single-task lists, but this overall cost was moderated by the presence of task cues and by the type of verbal memory load. Verbal load was varied in three levels: no concurrent verbalization; simple irrelevant verbalization, which required recitation of the months of the year (June, July, . . .); or cognitively demanding verbalization (i.e., the trails task, Lezak, 1983), which consisted of alternating recitation of the months of the year and the days of the week (April, Tuesday; May, Wednesday; June, Thursday; . . .). When task cues were shown, the alternating-list cost was present only when a concurrent demanding verbalization task was performed. Without cues, the alternating-list cost was present in the three types of verbal load, and the cost increased with the amount of load imposed by the verbalization task. These findings suggest that only a demanding verbalization interferes with task-switching performance, but that in the absence of external cues, participants spontaneously use verbalization (inner speech) to remind themselves of the present task, thus creating for themselves a demanding verbal dual-task situation.

Study of the role of inner speech was pursued further by Emerson and Miyake (2003). Using a similar design with arithmetic tasks (+3, −3) in single- and alternating-task lists, they confirmed that switch costs increased when the concurrent task was a verbal task (articulatory suppression: fast continuous repetition of "a-b-c") but not when it was nonverbal (foot tapping). Emerson and Miyake also varied the informativeness of the cues by including conditions without task cues, with nonspecific cues (colors; e.g., the number printed in red for addition), and with specific cues (+ for addition, − for subtraction). More informative cues resulted in smaller switch costs. However, at all levels of informativeness, the switch cost was larger in the conditions with articulatory suppression than the conditions without a secondary task (see also Saeki & Saito, 2004a; Saeki, Saito, & Kawaguchi, 2006, for similar results). These findings confirm that the requirement to perform articulatory suppression impairs the efficiency of verbal self-instruction via inner speech. Such verbal self-instruction is needed to support selection of the correct task and to update progress in the action plan in WM (see also Mayr & Bryck, 2005). Several studies have shown that self-instruction plays a similar role in other variations of the task-switching procedure, such as alternating runs of twice the same task (Saeki & Saito, 2004b), explicitly cuing the task (Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, 2005; Miyake, Emerson, Padilla, & Ahn, 2004), and cuing the transition (switch or nonswitch) rather than the task (Saeki & Saito, 2009).

In short, the studies on verbalization show that concurrent irrelevant verbalization impairs task-switching performance. These studies hence support the conclusion that maintaining a verbal goal representation plays an important role in task switching: when the cues are transparent, the verbal goal can be retrieved without any additional verbal processing, but when the cues are absent or nontransparent, additional verbal processing is needed to establish the verbal goal.[2] Inner speech may be used to support this maintenance, and it takes the form of verbalization of task goals, task cues, and possibly category-response mappings (Liefooghe et al., 2005; but see van't Wout, Lavric, & Monsell, 2013). Thus inner speech supports cue interpretation, particularly in situations in which the cues are arbitrary and do not provide direct access to the task name or the task goal (Miyake et al., 2004; Saeki & Saito, 2012). Inner speech also supports maintenance of the current goal and updating of a plan (i.e., replacing a previous task set by a new task goal and task settings; Bryck & Mayr, 2005).

Task-switching efficiency under WM load. The relationship between WM and task switching concerns whether and to what extent task switching and WM share executive control processes. This issue has been addressed in a rather small number of studies.

Logan (2004) addressed this question by directly comparing memory and performance measures. He estimated memory performance by means of the memory span, which is defined as the number of memoranda that can be recalled in the correct order on 50% of the trials. Lists of between 1 and 10 task names such as "high-low," "odd-even," or "digit-word" were presented for serial recall. For each length, the proportion of completely correct recall trials was registered, and the length corresponding to 50% correct performance yielded the person's memory span score. By the same logic, Logan defined the task span as a measure of task performance, namely, as the number of tasks that can be correctly remembered and performed in correct order on 50% of the trials. The same lists of task names were presented; when list presentation was complete, the participants were requested to apply the remembered tasks to a series of targets such as "3," "8," and "2" in the correct order (the first task to the first target, the second task to the second target, and so on). The list length corresponding to completely correct performance on 50% of the lists was registered as the person's task span. Despite the presence of frequent task switching in the task-execution condition, the task span and the memory span did not differ. Also a comparison between strict scoring (recall the correct task, and emit the correct response) and lenient scoring (recall the correct task, but allow an incorrect response) revealed no systematic differences between task spans and memory spans. Hence, no trade-off between maintenance and processing was observed in this setup (see also Logan, 2006, 2007), and this result suggests that no capacity must be shared between task performance and task switching on one hand and maintenance of task information on the other.

Kane, Conway, Hambrick, and Engle (2007) reached a similar conclusion in a correlational study in which they investigated task-switching performance by comparing participants with high and low complex-span tasks. Complex span tasks measure the amount of information that one can retain while concurrently executing another task, for example, remembering a series of digits while performing a series of arithmetic operations (operation span, Turner & Engle, 1989). Switch costs were present in both groups, but the size of the switch cost did not differ across high- and low-span subjects. In the same vein, a structural equation modeling study showed no commonality between task switching and memory (Oberauer, Süss, Wilhelm, & Wittman, 2003). Furthermore, presence of a memory load does not seem to affect task-switching performance (Kiesel, Wendt, & Peters, 2007). Hsieh (2002) found that a concurrent arithmetic task impairs task switching; however, Kessler and Meiran (2010) reported no effect of a numerical judgment task on task-switching performance. The contrast between the latter two findings may be due to the larger verbal load present in an arithmetic task (e.g., Imbo & Vandierendonck, 2007).

The thrust of these findings is that although WM may play a role in task switching (as shown by the verbalization studies), task switching and WM do not seem to call on a common limited-capacity resource. In other words, the limited-capacity resource needed to maintain the task names is not needed for the control processes involved in task switching, as is most clearly corroborated by the task-span findings of Logan (2004). However, it may be that the common practice of separately measuring latency and accuracy switch costs results in an underestimation of the true switch cost, in particular in situations in which variations in speed-accuracy trade-off may play a role (Hughes, Linck, Bowles, Koeth, & Bunting, 2014).

Goal selection under WM load. The third research question about the relationship between WM and task switching concerns the role of WM in task selection. Instead of receiving instructions on which task they should perform on each trial, in the voluntary task-switching (VTS) procedure, subjects voluntarily select the task they will perform (Arrington & Logan, 2004, 2005). In addition to the usual performance measures (accuracy, speed, and the associated switch costs), this procedure allows researchers to measure task frequency and task-switch frequency. In almost all VTS studies, investigators have reported a *task repetition bias* (i.e., a bias toward selecting a task repetition over a task switch). This bias becomes smaller when there is more time to prepare (Arrington & Logan, 2005) but is also influenced by external factors (Arrington, 2008; Arrington & Rhodes, 2010; Mayr & Bell, 2006; Weaver & Arrington, 2010). Clearly, VTS is also vulnerable to interference effects (Mayr & Bell, 2006; Yeung, 2010). Nevertheless, VTS leaves more room for endogenous control than the standard task-switching procedures do (Arrington & Logan, 2005; Liefooghe, Demanet, & Vandierendonck, 2009).

To date, only a few studies have addressed the role of WM in VTS. Weaver and Arrington (2010) presented a letter and a digit on each trial and allowed the participants to perform either a consonant/vowel decision on the letter or an odd/even decision on the digit. During the execution of these tasks, WM was loaded with three symbols (mixture of letter and digits) at three specific locations. The letter or the digit presented on each trial either matched one of the three symbols or one of the three locations represented in WM; the other symbol did not match an identity or a location of the elements in memory. Participants more frequently selected the task applicable to the symbol that matched the memory contents, suggesting that the overlap between the target and WM tends to activate the associated task, making it more available.

Demanet, Verbruggen, Liefooghe, and Vandierendonck (2010) investigated how a six-item memory load modulated the effect of bottom-up interference on the repetition bias in VTS. Under conditions of interference, the presence of a memory load resulted in a larger task repetition bias. The investigators varied three types of bottom-up interference: stimulus repetitions, repetition of irrelevant stimulus features, and stimulus-task associations. Only in the case of bottom-up interference with stimulus repetitions was the effect of the memory load larger when the stimulus actually repeated than when it changed. This finding supports the view that top-down control counteracts the automatic tendency to repeat tasks (Vandierendonck, Demanet, Liefooghe, & Verbruggen, 2012) and shows that the presence of a WM load makes the top-down control less efficient.

Butler, Arrington, and Weywadt (2011) examined the effect of stimulus repetitions in an individual differences approach. Task repetition bias did not correlate with WM capacity as measured by the operation span (Turner & Engle, 1989). In contrast to the previous study (Demanet et al., 2010), Butler et al. (2011) used less frequent stimulus repetitions, and there was no memory load to augment the difficulty of interference resolution.

Conclusion. A few conclusions can be drawn from this brief review of studies on the relation between task switching and WM. First, the studies on the role of relevant and irrelevant verbal memory loads and the informativeness of the task cues show that maintenance of the task goal depends on verbal WM and inner speech. Therefore, goal representation and maintenance require verbal WM. Second, the findings that memory span and task span do not differ (Logan, 2004) and that task-switching costs do not vary with WM capacity (Kane et al., 2007) show that maintenance of declarative information does not interfere with task execution and task switching. Although representation of the goal name does require verbal WM, it does not create an extra burden on task-switching performance because such goal representation is probably present for any task that is being executed. Therefore, it seems that the contribution of working WM to task switching is not in providing extra (verbal) storage but rather in providing another kind of resources. Jointly with the findings in voluntary task switching that a memory load and its maintenance result in less efficient coping with bottom-up intrusions, the contribution of WM to task switching seems to consist of providing facilities to implement and maintain the task set, selecting appropriate means to attain the goal, and biasing the competition between goal-relevant and goal-irrelevant processes toward goal attainment.

Constraints from dual-task research

WM research heavily relies on dual-task methodology. Only a few studies are relevant to the issues at stake here, and in all of these studies, the methodology used was inspired by the time-based resource-sharing (TBRS) model of WM (Barrouillet et al., 2004). Memoranda are presented one by one for later serial recall, and after each memorandum or after a series of memoranda, a retention interval that can be used for rehearsal or refreshment is filled with strictly timed tasks that differ in the amount of required cognitive control. These studies converge on the finding that when the interval is filled with tasks that require more executive control, serial recall of the memoranda is poorer (Barrouillet, Bemardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet et al., 2004; Barrouillet, Lépine, & Camos, 2008; Barrouillet, Portrat, & Camos, 2011; Oberauer & Lewandowsky, 2011; Portrat, Barrouillet, & Camos, 2008; Vergauwe, Barrouillet, & Camos, 2010). More executively demanding tasks usually take longer to perform and occupy central attention (or the central executive) for a longer time than less demanding tasks. All these studies show that the same central attentional resource is involved in serial memory performance as in cognitively demanding tasks.

In the present context, it is interesting to have a closer look at one study in which the same methodology was used to investigate whether task switching also calls on the same central attentional resource. Liefooghe, Barrouillet, Vandierendonck, and Camos (2008) varied the number of task switches during the retention/rehearsal interval while keeping all other task parameters constant. On each trial, a list of letters was presented for serial recall, and in the interval between presentation and recall, a series of digit-categorization tasks (magnitude and parity judgment) were performed under strictly timed conditions. Across and within several experiments, the number of switches in the series of digit categorization tasks varied. This procedure was based on the hypothesis that switch trials involve task reconfiguration and interference control so that series with more switches impose a larger cognitive load. As predicted, when more switches were required during the maintenance interval (higher cognitive load), serial recall was impaired. In the reverse direction, the size of the memory load did not affect the switch cost.

Together with other published studies, the studies reviewed here show that the WM system provides domain-general support that is needed for memory maintenance (in particular, serial recall) as well as for execution of intentional tasks. If one assumes that the attentional resource operates in an all-or-none fashion and can only serve one task at a time, then it would seem that larger the amount of time in the retention/rehearsal interval that is occupied by attention-demanding tasks, the smaller the amount of time that can be invested in rehearsal or memory refreshment activities, and the poorer serial recall will be.

An Adapted WM Architecture

This brief overview regarding interactions of WM and task execution in the context of task switching and dual tasking provides important and useful information for refining the conceptualization of WM. I now use the implications and restrictions that follow from this overview to build a new multicomponent model of WM. This new model retains the components of the old model that have proven to be most useful, namely, the phonological loop, the visuospatial sketch pad, and the episodic buffer; the central executive is replaced by more appropriate components.

The first conclusion drawn from the overview shows that WM maintains a goal representation during task execution. The sensitivity of this goal representation to both facilitation and interference from external verbal and phonological activity suggests that the goal is likely to be maintained within the verbal storage system (phonological loop). However, as I argue in a later section, goal-directed responding requires binding of the goal representation to other WM contents; if binding is needed, the episodic buffer would seem more appropriate.[3]

Second, both task-switching and dual-task research show that a task set must somehow be kept active in WM during task performance. However, because the task span (remembering the task names and executing the tasks) does not differ from the memory span (remembering only the task names), it is evident that the task set is not maintained in domain-specific (verbal or visuospatial) storage. Nevertheless, the task execution modalities and constraints must be stored in some part of the WM system.

Executive memory module

Because the central executive in the multicomponent model is a processing unit and not a memory store, the task set cannot be simply maintained in this module. As suggested by Duncan et al. (2008) in their research on goal neglect (the failure to attain the goal due to the failure to attend to goal-relevant environmental features), a task model (information about task execution modalities and restrictions, i.e., the task set) could be maintained in the episodic buffer throughout task execution. However, in consideration of the conclusions drawn from the overview of findings, this option is not plausible because information maintenance in WM does not interfere with task execution. Moreover, in combination with the finding that executive control is not implied in the binding performed via the episodic buffer (e.g., Baddeley et al., 2009), it seems that the episodic buffer cannot satisfy this role. In other words, neither the domain-general nor the domain-specific parts of the multicomponent WM model provide a facility that is suitable for maintenance of the currently active task sets. Therefore, in addition to the phonological loop, the visuospatial sketch pad, and the episodic buffer, the multicomponent model of WM should be equipped with a dedicated storage component for the maintenance of the currently and recently active task sets. The *executive memory* (EM) component is proposed to fulfill this role. The rationale is that every goal-directed activity needs a memory trace of the goal, of the means to achieve the goal, and of the restrictions and constraints in the situation at hand. As intentional memory and recall are goal-directed activities, it would seem that these activities are also supported by an active goal representation and a task-set representation and that alternation between task execution and memory refreshment involves a task switch; the switch has a rather small cost because the degree of overlap between memory refreshment and a cognitive task is likely to be much smaller than the overlap among the cognitive tasks typically used in task-switching research. Because of this difference in task overlap, memory refreshment and a cognitive task can be more easily coordinated in a common plan (Lien & Ruthruff, 2004; Logan, 2007; D. W. Schneider & Logan, 2006).

Figure 2 shows this new EM as one of the modules placed at the same level as the other storage modules (phonological loop, visuospatial sketch pad, and episodic buffer). The EM module is shown to interact with long-term memory (LTM), the episodic buffer, and the phonological loop. As previously discussed, during task execution, EM is assumed to contain a representation of the task set. This information encompasses S-R mapping rules; a number of task-relevant settings, such as orientation of attention (Gopher, Armony, & Greenshpan, 2000),[4]

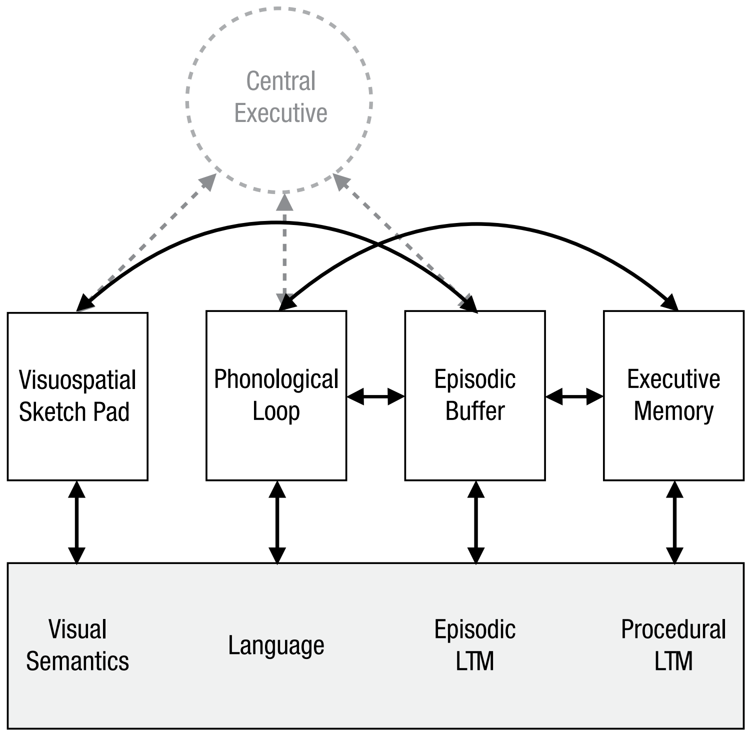

Fig. 2. Architecture of the modified multicomponent working memory framework. The modified model is shown in black and consists of the new components and the part of the original model that is retained; the remainder of the original model is shown in gray. The central executive (gray) is replaced by the executive module (black) that connects to the episodic buffer, the phonological loop, and long-term memory (LTM) and by a distributed control network that consists of the knowledge base in procedural LTM (black) and a processing engine (not shown because it connects to all the components).

response threshold, and response bias (Logan & Gordon, 2001); and also some task constraints that are often specified in the task instructions, such as stimulus modality (Hunt & Kingstone, 2004; Murray, De Santis, Thut, & Wylie, 2009) and response modality (Koch, Gade, & Philipp, 2004; Philipp & Koch, 2005). After the task is finished, these elements are no longer kept active and can be actively inhibited if necessary. The EM module is a passive system in the sense that it only maintains information for as long as it is needed, and although this system is assumed to have limited capacity, it can contain more than one active task set as long as the task sets do not interfere with each other. The possibility that more than one task set can be active in EM is considered to be important when several tasks have to be coordinated as in the context of complex skill acquisition. How many task sets or task-set components the module can contain is an empirical question but in practice also will depend on the degree to which the active task sets are in a competitive relationship.

Figure 2 also shows that the EM connects to procedural LTM. The rationale for this connection is that EM contents are filled in on the basis of procedural knowledge available in LTM. As in typical production models (e.g., Kieras, Meyer, Mueller, & Seymour, 1999; Lovett, Reder, & Lebiere, 1999; W. Schneider, 1999), procedures stored in LTM are assumed to take the form of condition-action rules: "IF condition, THEN action" (e.g., "IF digit is even, THEN remember digit category even"). Rules that match information in the storage systems of WM become activated, and their action parts are executed, which sometimes consist of storing additional information in WM.

Because of this link to procedural LTM, the EM is similar but not identical to the procedural WM component proposed by Oberauer (2009) in his WM model. In the latter model, the WM is assumed to consist of activated LTM. Parallel to the distinction between declarative and procedural LTM, this model distinguishes between a declarative and a procedural WM module, so that procedural WM is the activated part of procedural LTM, just as declarative WM is the activated part of declarative LTM. However, if declarative WM is simply activated declarative LTM, it would not possible to distinguish between different occurrences or activations of the same event. For example, to have an appropriate representation of "One boy came, and another boy left," one must be able to distinguish the first occurrence of "boy" from the second occurrence. With a WM that is only activated LTM, this distinction cannot be made. This difficulty is overcome if one assumes that generic elements (types, e.g., the concept of "boy") are retrieved from LTM and transformed into specific instances (tokens) by the addition of input and context information (e.g., boy_1). This transformation process is called *instantiation*. A consequence of the assumption that LTM contains types and WM contains tokens is that WM is considered to be a temporary store linked to but separate from LTM. For procedural LTM, the situation is slightly different. Because procedural LTM contains procedural rules, activation of these rules executes the action part of the rules. As a consequence, EM in the present model contains representations that result from the actions performed when procedural rules are activated.

Another important difference relates to the symmetry in Oberauer's model between the declarative and procedural WM components; these components are structured in a strictly similar and symmetric way, so that in both components, the most activated element is in focus (focus of attention, response focus) and is part of a set of highly activated elements composing a subset of the activated LTM elements. Such a strict symmetry makes it difficult to define operational distinctions between procedural and declarative WM because the elements in declarative WM have to be linked to operations represented in procedural WM; thus, degree of activation of an element in one module tends to go hand in hand with the degree of activation of the linked element in the other module. There is no compelling reason to assume that declarative memory and procedural memory operate in strictly similar ways; therefore, in the present model, no symmetry is assumed between EM and the other modules that contain declarative information. Finally, in contrast to procedural WM that only contains the S-R mappings, EM also contains other task-set parameters and constraints.

Distributed executive control processes

Figure 2 shows the central executive as part of the original model, but this component is not a part of the new WM architecture displayed in this figure; the adapted model does not contain a central executive or another autonomous agent that manages executive control or supervises the distribution of the attentional resource over different tasks. Nevertheless, the system must include a mechanism that ensures that intentional actions result in goal achievement. Although EM maintains task-relevant settings, it is just a memory store and is not equipped with any control mechanisms. In the present model, executive control is proposed to result from processes in a distributed procedural knowledge network. Within this network, a procedural knowledge base (procedural LTM) contains rules that can be triggered by the contents of WM. A processing engine then executes the actions specified in the selected rule. How this result is achieved and how it can account for executive control is explained in the following section.

Procedural knowledge base. The procedural knowledge base consists of condition-action rules. These rules can be quite simple, such as "IF number is even, THEN press right button" or "IF a plus cue is present, THEN instantiate 'addition of 1' as the goal," but they can have rather complex condition parts such as "IF the goal is parity judgment AND the number is 3, THEN categorize the number as odd," or "IF a plus cue is present AND the goal is subtraction, THEN suppress the subtraction goal," or even "IF a goal is addition and a goal is subtraction, THEN set the goal-conflict flag." These examples show that when applied, some of these rules initiate a motor action (e.g., "press right button"); others update WM contents either directly (e.g. "suppress subtraction goal") or after performance of a cognitive action (e.g., "categorize as odd"); still others may simply change a parameter setting in the task set (e.g., "set goal-conflict flag").

The rules in these examples have all been acquired. Although some procedural knowledge is innate (e.g., "IF pain is felt, THEN cry," or "IF feeling hungry, THEN eat"), most of this knowledge is acquired from experience and practice, but rules can also be acquired by instruction (Cohen-Kdoshay & Meiran, 2007). Procedural learning occurs in a number of ways: by adapting the rule strength of existing rules, creating completely new rules, or combining existing rules. Each production rule has a *strength* or *confidence value* that changes on the basis of experience: the more often a rule has been successfully applied, the more the confidence in the rule has accumulated; similarly, after unsuccessful application, the confidence decreases. Creation of a new production rule occurs if the current WM content is taken as the condition and the produced output is taken as the action. For example, when the answer "5" in response to the attended stimulus "2 + 3 = ?" is rewarded, the rule "IF goal is to add two numbers AND the sum of 2 and 3 is requested, THEN say 5" may be created. Initially, this rule will have a rather low confidence value, so that the likelihood of its being activated is rather low. However, when one must solve the same problem again, the rule may be recreated, leading to an increased rule strength. After a sufficient number of successful rule applications, the rule may have gained so much strength that it always gains the competition. As discussed previously, it is well known that during execution of simple cognitive tasks, new S-R rules (in line with Pashler & Baylis, 1991a, 1991b) and new stimulus-task rules (in line with Waszak et al., 2003, 2004, 2005) are created. Apart from these two elementary forms of rule learning, a new rule also can be created by combining existing ones. If two rules with the same action part have conditions that differ, a new rule encompassing both conditions may be created, which results in a more general rule. This possibility is important in categorization; use of the rules "IF there is a square AND its color is red, THEN say Category A," and "IF there is a square AND its color is blue, THEN say Category A" forms the more general "IF there is a square AND it has any color, THEN say Category A" (e.g., Anderson, Kline, & Beasley, 1979). Other possible rule combinations may result in rule specialization or even in the creation of chained rules.

Processing engine. The procedural knowledge base in LTM can thus be characterized as a repository of procedural rules. A processing engine handles the activation and selection of the relevant rules. Only when the condition part of a rule matches one or more WM contents, the rule can be applied. The rules that match WM contents are flagged as applicable, and from this applicable set, only the most relevant rules are allowed to fire, which means that their action part is executed.

How can it be determined that one rule is more relevant than another one? Assessment of relevance may depend on several features. Rule strength is a first possible feature. A rule with a high strength or confidence value has proven to be successful and therefore may be considered to be more relevant than rules that have accumulated less strength. However, even when a rule has built up strength in a particular context, it may be less relevant for the present context than a weaker rule. For example, the more general rule "IF it is cloudy, THEN it will rain" may be stronger than the rule "IF it is cloudy and it is freezing, THEN it will snow"; however, if both match, the latter rule would be more relevant because it applies to more specific conditions. For that reason, rule specificity also should be taken into account on the assumption that a more specific rule is more likely to be useful in the present context than a more general rule (see also Holyoak, Koh, & Nisbett, 1989). This point can be clarified by comparing a few examples: "IF category is even, THEN press right button"; "IF goal is parity AND category is even, THEN press right button"; "IF goal is parity AND number is 4 AND category is even, THEN press right button"; and "IF binding contains parity goal AND number 4 AND category even is present, THEN press right button." These examples have all the same action part, but they differ in the generality of the conditions so as to form a hierarchy. The fewer elements that are specified in the condition, the more general the condition is; conversely, the more elements the condition contains, the more specific it is. The last rule in this list of examples is very specific in that it specifies the current goal, the digit, its categorization, and the existence of a binding of these elements. If all these components are present in WM, then it is quite likely that this rule is relevant to the presently existing context. In contrast, the first example in the series only mentions the category "even." Although the rule has some relevance, it is far less specific because it also would match when another goal is present and the category representation in WM is a leftover from a previous event.

A further feature that can be used to assess relevancy is the degree of match. In many production systems (e.g., Anderson et al., 1979), matching is either all or none, but it is perfectly possible to consider matching as a matter of degree (e.g., Vandierendonck, 1995); a higher degree of matching corresponds to a higher degree of relevance of the rule. In sum, the rules selected to be most relevant will be the ones with the highest confidence value, the highest degree of match to the existing conditions, and the most specific conditions for the same proposed action.

Checking of WM contents for applicable procedural rules occurs according to a scheduled process. To that end, the processing engine performs a continuously cycling processing loop consisting of a series of actions, including processing of environmental inputs, checking for conflicts, adapting WM contents, and initiating motor actions. In every cycle, some procedural rules that match WM contents are applied. Each rule application takes some time, so that the next cycle of checking can only start after rule application has finished. It is also important to note that not every rule applied contributes to achieving the intended goal. For example, some rules provide a shortcut between stimulus and response, actually bypassing the task set specifications. When other processes do not block the bypassing action, an action slip (error) is bound to occur.

Conclusion

The model proposed here is a modification of the multicomponent model of Baddeley and colleagues (Baddeley, 2000; Baddeley et al., 2010; Baddeley & Hitch, 1974). This modification retains the modality-specific storage systems (phonological loop and visuospatial sketch pad) and their relation to LTM via either a direct route or the episodic buffer, which is a multimodal store that binds information from the modality-specific storage systems and LTM. The modified model does not include the central executive but instead provides a temporary store to maintain task-relevant settings. This store is directly linked to procedural LTM. A processing engine selects relevant procedural rules that match WM contents and executes their action parts.

Contribution to Executive Control

How can this proposed system, which operates on the basis of rules that are automatically triggered when their conditions match WM contents, explain what is usually called executive control? Executive or cognitive control and automatic processing often are considered to be two qualitatively distinct forms of processing. Typically, the difference between controlled and automatic processing is assumed to be characterized as three qualitative dichotomies. Controlled processes are capacity limited, occur under intentional or planned control, and are used with an awareness of the outcomes, whereas automatic processes are not capacity limited (and hence do not suffer from interference), occur under stimulus control, and are not used with an awareness of outcomes (Neumann, 1984). Nevertheless, empirical findings rather suggest that there is a continuum from automatic to controlled processes (e.g., W. Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In particular, it should be noted that actions that are executed for the first time often require important amounts of control, but with practice, execution becomes more automatic (Shiffrin & Schneider, 1977). With learning and practice, new connections are formed and strengthened. While initially the link among stimuli, representations, and responses have to be retrieved separately and then bound together, with practice the LTM association among these components gets stronger. As a result of practice, a transition occurs from separate retrieval and temporary storage of components to retrieval of a united representation. The advantages conferred by this transition are that the call on temporary storage decreases and thus bypasses the capacity limitation and that execution becomes faster and thus diminishes the chances of interference by other fast (bottom-up or stimulus-driven) processes. In essence, due to learning and practice, there is a shift from intentionally driven to more stimulus-driven control. With more automatization or more stimulus-driven control, task execution becomes easier.

Task difficulty does not depend only on the degree of automatization but also on the number of actions or the complexity of the actions that must be performed. Hence, task difficulty is often reflected in the complexity of the task set in terms of number of rules, parameters, and constraints. Repeating out loud the syllable "blah" at a fast pace (articulatory suppression) is an example of a quite simple task that does not require control processes once the recitation is started. In contrast, counting backwards by 3 (191, 188, 185, and so on) is an example of a more difficult, nonautomatized task. After encoding the starting number in WM, one must apply a subtraction, then replace the number in WM with the result of the subtraction, and then continue executing the same sequence over and over. As more action components are added, the task grows in difficulty, and this increasing difficulty goes hand in hand with increased amounts of intentionally driven control processes.

Related to the contrast between automatized and nonautomatized tasks is the distinction between intentional contexts in which the route to the goal is known and intentional contexts in which the route to the goal is not yet known. In the former category, the action reproduces the achievement of a goal that has been reached previously; therefore, this action can be referred to as *reproductive goal achievement*. In the latter category, the means to achieve the goal still have to be found and produced; therefore, the action can be referred to as *productive goal achievement*. Because this constitutes a real dichotomy with qualitative differences between the two categories, these two cases are considered separately.

Control in reproductive goal achievement

To understand how the procedural network in interaction with WM contents can account for what is usually called executive control, one must remember that each intentional action requires an instantiation of the intention or goal and the retrieval and configuration of the related task set in WM. Because this is the context of reproductive goal achievement, the task set (i.e., the way to achieve the goal and the constraints in doing so) must be assumed to have a representation in LTM. I explain how the system accounts for executive control in three different cases: task switching, a memorization task, and a dual-task context involving both memorization and task execution.

Task switching. In many studies of task switching, researchers have investigated switching between numerical judgment tasks, such as parity and magnitude judgment (e.g., Logan & Bundesen, 2003). These tasks were included in examples presented earlier in this article. To illustrate how control processes are conceptualized in the present model, I have used these tasks again. In the present case, each trial starts with the presentation of a digit shown either in blue (signaling the magnitude task) or in red (calling for the parity task). The parity judgment task requires a left key press for an odd number and a right key press for an even number; the magnitude judgment task requires a left key press if the number is smaller than 5 and a right key press if the number is larger than 5; the digits are centered on a screen; responses are expected to be fast but correct. All this information is presented in the instructions and is stored in LTM. Notwithstanding evidence suggesting that an immediate procedural encoding occurs (Cohen-Kdoshay & Meiran, 2007; Liefooghe, De Houwer, & Wenke, 2013), some practice is included to stabilize the procedural encoding of all this information.

Each trial of the experiment starts with the appearance of a digit in the center of the screen—say, for example, a red digit 3 on the current trial. As the appearance of the digit involves a change in the visual environment, it (automatically) captures attention. This capture leads to its instantiation in WM, presumably in the episodic buffer but possibly also in the phonological loop.[5] The color feature of the digit matches the rule that translates the color into a goal ("IF color is red, THEN select parity goal"), which results in the instantiation of the goal name in the episodic buffer. Next, the task set is retrieved from procedural LTM and configured in the executive module. The present example includes two category-response rules ("IF odd, THEN press left," and "IF even, THEN press right"), a parameter setting that a manual motor response is required, and a parameter setting that both speed and accuracy are required. Thus far, the WM contents match rules regarding parity goals, parity task sets, and digits. The combination of goal and digit matches some rules, for example, a rule such as "IF goal is parity and digit is 3, THEN retrieve category odd." If this rule is applied, the digit parity (odd) will be added to the episodic buffer. On a next processing cycle, the presence of the goal, the digit (target), and the category may trigger a rule to create a binding of these elements in the episodic buffer. This binding may then trigger a rule to activate the corresponding response rule that is part of the task set. After sufficient activation has been accumulated, a left key press response will be executed. This sequence of processes corresponds to Pathway 1 of Figure 1, and involves both the episodic buffer and the executive memory module.

With more practice in the task, the LTM rule linking the digit and the parity category becomes stronger and may be triggered automatically, resulting in simultaneous instantiation of the digit and its parity category in the episodic buffer (Pathway 2 in Fig. 1). Thus, the time needed to complete processing of the target is shortened, with as a consequence faster correct responding.

When the category "odd" is instantiated in the episodic buffer, irrespective of whether this occurs due to activation of the shortcut just mentioned or whether the category is retrieved on the basis of the combination of digit and goal, an error may occasionally occur. For example, when the present digit (3) and the category "odd" are in the episodic buffer while the previous category ("even") is still present, both the triplet "parity goal, 3, odd" and the triplet "parity goal, 3, even" meet the conditions of a rule to form a binding. Only one of those bindings can be implemented because each particular element can be present in only one binding at any time. Whichever of the two bindings is implemented first will constrain further response selection. In other words, if the parity-3-even binding is implemented first, the even-right rule in EM will be triggered, even though the present digit is odd." This example shows that the processes involved in binding the WM elements are "blind" to the precise features of their inputs and hence do not "know" which binding is the correct one.

In contrast to repeat trials (trials in which the task or goal remains the same), switch trials require retrieval and configuration of a different task set, which makes performance vulnerable to sources of interference such as target-response associations and target-task associations. In typical task-switching contexts, all the targets are randomly distributed over the tasks, so that each digit occurs about equally frequently in each task. Thus, if an association between a particular digit and a specific task is formed, the association between the same digit and the other task are roughly equally strong, so that there is no real danger of such an association bypassing processing. Similarly, if an association between a particular digit and a correct response under a particular task is formed, the association between this digit and the alternative response has a similar strength. The likelihood that such an association bypasses processing is also rather small.

Nevertheless, it is worthwhile to explore what would happen if such associations could acquire enough strength to affect performance. First, I examine the case of a target-response association (Pathway 3 in Fig. 1). Consider the case that over a series of magnitude judgment trials, an association between the digit 7 and the response right (IF digit 7, THEN respond right) has built up strength and that the present trial shows the digit 7 in a parity task. If the association has sufficient strength, the right key press may be gaining strength while instantiation of the parity goal and the corresponding task-set reconfiguration still have to be completed (as in Pathway 1 of Fig. 1). If the strength of the respond-right process reaches threshold before target-related processing is complete, an incorrect and, in fact, unintended response will be made. The only way to safeguard against such fast errors is to make it more difficult for the unintended response to be made by raising the response-threshold setting (in EM) so that responding overall becomes slower.[6] This extra time before responding completes allows goal-directed processing to configure the task set and to build up strength in favor of the correct response. The result is that on some occasions the incorrect response will be executed while on other occasions the correct response will be produced.

Next is the case of target-task associations (Pathway 4 of Fig. 1). This case is based on the acquisition of an association between the target digit and the task name ("IF digit 7, THEN instantiate magnitude goal") within the context of the same example of the digit 7 occurring only in the magnitude task over a series of trials. When the digit 7 occurs while the magnitude task set is already configured, application of the rule only strengthens the present goal and task-set representations. However, if the digit 7 is presented for parity judgment (as indicated by its color), two incompatible goals may become instantiated in the episodic buffer: the parity goal (on the basis of the color cue) and the magnitude goal (on the basis of the acquired association). These instantiations will be accompanied by instantiation of the corresponding task sets in EM. The presence of incompatible goals in the episodic buffer or incompatible task sets in EM constitutes a goal conflict. If a conflict-detection rule fires in response to the goal conflict, a goal-conflict flag is set because further processing of two incompatible intentions is bound to result in incoherent responding. As a safeguard, when the goal-conflict flag is on, only goal- and task-set-relevant rules are allowed to fire. When the conflict is resolved, the conflict flag will be turned off. In the meantime, only goal instantiation, goal inhibition, and task-set-configuration rules are allowed to fire, with the result that one of the two goals wins the competition. Because goal and task-set instantiations of both tasks start at about the same time, either of the two may win the competition, resulting in either a slow correct or a slow incorrect response.

This account of the rule applications in a task-switching context shows that there is no need for a special agent to control the events and actions. Instead, in the four processing pathways that have been well documented by previous task-switching research, the actions performed are completely accounted for by the contents of the WM modules and the rules available in procedural LTM. Because the rules vary in strength, the time course of WM instantiations shows some variation, resulting also in variable responses and response times. So, even though the interaction of conditions and rules follows fixed principles, the resulting behavior of the system still is variable.

Intentional memorization. Although memorization without explicit intention to retain the information for later usage does occur, in the context of WM research with its focus on serial recall, storage is driven by an intention to use the stored information. Because of this intentional basis, this activity is assumed to involve, like any other intentional activity, a representation of the memorization goal and a corresponding task set. Given that the task set specifies the means to attain the goal, it seems evident that the task set encoded in EM would include one or more of the "strategies" that could be used to efficiently store and maintain information in memory, such as encoding, chunking, grouping, rehearsing, or refreshing. To cope with anticipated requirements of recall (e.g., a focus on item information, particular item features such as location or color, or the serial order of items), one selects a suitable memorization method, and it is encoded in the task set. Other task constraints such as expected modalities of recall also are part of the configured task set.

The presence of a memorization intention thus affects the maintenance operations performed during a retention interval. In a typical WM task, serial position of the memoranda is important, so rehearsal and refreshment have to respect order coding. Similarly, if chunking is used, the chunks have to respect the order of the individual memoranda.

Once the memorization goal and task set are prepared, each occurrence of a new memorandum has to be stored in WM in accordance with the memorization rule and parameters specified in the task set. In the interval between successive memoranda and during the retention interval at the end of the list of memoranda, some operations are performed to enhance the likelihood of later retrieval of the memoranda. These operations are specified in procedural LTM and result in different actions depending on the modality of the memoranda. For memoranda stored in the phonological loop, regular rehearsals are performed, whereas for memoranda in the episodic buffer, refreshments are more likely to be used (for more details about this difference, see Camos, Lagner, & Barrouillet, 2009; Camos, Mora, & Barrouillet, 2013; Camos, Mora, & Oberauer, 2011; Mora & Camos, 2013).

When recall is requested, the memorization goal is replaced by a recall goal and corresponding task set. This task set specifies the output modality required for recall (oral recitation, written recall, old/new decision, and so on). A recall loop is started, such that in each cycle of the loop, the WM contents are scanned, and the memoranda recovered are encoded in the output buffer and eventually emitted.

Dual-task: Task execution during retention interval. The model's account of the control processes occurring in a dual-task context involves both memorization and task execution. In the case considered here, a series of tasks must be performed during the retention interval of a memorization task. Many dual-task studies have reported an impairment of serial recall when a secondary task is performed during the encoding interval, the retention interval, or both. Controlling for time available for memory maintenance and secondary task execution, the methodology introduced by Barrouillet et al. (2004) has become a standard in the field to test TBRS theory. A simple experiment reported in Barrouillet, Portrat, Vergauwe, Diependaele, and Camos (2011) is used here to illustrate how the model accounts for control processes in such a dual-task setting.

In this experiment, memoranda were seven consonants, each followed by an interval during which either four or eight squares were presented at a slow (1,190 ms per square), medium (990 ms per square), or fast pace (790 ms per square). The participants judged whether the location of the square was above or below the screen center. In the theory tested in this experiment, memory refreshment and task execution are assumed to require attention, which is a resource that can be shared in an all-or-none manner among different tasks. Hence, during the retention interval, attention allocation rapidly switches between the location decision tasks and memory refreshment. That means that while attention is occupied by the location decision task, attention is not available for memory refreshment: The larger the proportion of the retention interval that is occupied by decision tasks, the smaller the proportion of time that will be left for memory refreshment, and the more recall will be impaired. As expected on the basis of the theory, recall was poorer with faster presentation rates, but the number of squares in the interval did not affect recall performance because the cognitive load (proportion of the interval occupied by the decision tasks) did not change.

How does the present model account for such findings? At the start of each trial, the memorization goal is instantiated in the episodic buffer, and the memorization task set is configured in EM. Next, the first memorandum is presented and encoded in the episodic buffer. Soon after encoding and refreshment have started, the first square is presented. As appearance of the square constitutes an environmental change, attention is captured, resulting in the instantiation of the location-judgment goal in the episodic buffer and configuration of the corresponding task set in EM. With this shift from memorization to location judgment, the memorization task set must be inhibited. However, the amount of inhibition applied to the memorization task set can be assumed to be limited because the memorization rules and the location-judgment rules respond to different conditions, so that there is little opportunity for overlaps between application of the memorization and the location-judgment task sets. As a consequence, the chances for mutual interference are rather small, and it suffices to ensure that the location-judgment task set is more strongly activated than the memorization task set. Furthermore, execution of the memorization task has to continue afterwards, so that it is more advantageous to keep the memorization task set in WM so that it can be swiftly reactivated when the opportunity arises. In fact, the context of the retention interval may be considered as one in which the memorization task is interrupted in favor of execution of another task.

When the location-judgment task set becomes the dominant one (i.e., is more activated than the memorization task set), the location of the square must be judged. The features of the square (form and location) become encoded in the visuospatial sketch pad, procedural rules to determine the location with respect to the reference become active, and the result of the process is a categorization response ("above" or "below") that is instantiated in the episodic buffer, where it can be bound with the goal and the target to activate the appropriate task-set rule (e.g., "IF a square is above center, THEN press left key"). After response execution, application of a rule matching the condition that a response has been emitted reactivates the memorization goal and task set and suppresses the no-longer-relevant location-judgment goal and task set so as to make the memorization task set dominant. The memoranda are now further refreshed until the next square is presented, which leads to a switching back to the location-judgment task. The remainder of the trial entirely consists of such switching back and forth between the memorization and the square-judgment task, and this switching continues until the next memorandum is presented or recall is requested. This state of affairs involving task-set switches ensures that the two tasks are performed strictly sequentially: No memory refreshments occur during location judgment, and no square processing occurs during memory refreshment. Without any need for additional assumptions, it follows that if more of the interval is occupied by location judgment, less time will be available for memory refreshment and that consequently more memory loss may occur. Clearly, this account makes the same prediction as Barrouillet's TBRS theory. Moreover, this prediction can be made without any call on a central executive or an attentional resource.

Interim conclusion. Clearly, for the all situations considered here, goal achievement is possible without an autonomous agent such as a central executive. In all the examples, the conditions represented in WM are sufficient to trigger specific condition-action rules that either change WM contents or initiate a response that achieves the goal. Occasionally, shortcut rules may be applied that sometimes result in the selection of an incorrect action or lead to a conflict that must be resolved and again may result in an error. In fact, the presence of such rules provides a more straightforward explanation of the occurrence of errors than a central executive that fails on some occasions.

Control in productive goal achievement

In a situation in which one lacks experience or in which the route to the goal is unknown, activation and instantiation of the goal will not result in a successful retrieval of a complete task set because the task set has not been learned yet. Finding a method to attain a goal is the context of problem solving. Even in the early days of the information-processing approach to cognition, this was the subject of computer-simulation programs such as the Logic Theorist (Newell & Simon, 1956) and the General Problem Solver (Newell & Shaw, 1959). These programs solve problems by searching the so-called problem space for combinations of means that lead to the goal. In terms of goals and task sets, this means that at first, a subgoal acts as a substitute for the goal during a search of the problem space (Newell, 1981) for a suitable way to achieve the goal. Usually a solution consists of finding one or more intermediate goals that can be achieved. For example, if the goal is to find the sum of 324 and 489, a subgoal first may be set up to find the sum of the hundreds (300 + 400), next the sum of the tens (20 + 80), then the sum of the units (4 + 9), and finally the sum of all the intermediate results. In general, a solution can be obtained by finding intermediate steps that can be achieved by already acquired means and then stepwise by applying the solution steps to reach the final goal (see also de Groot, 1965). The pioneering work of Alan Newell, Herbert Simon, and others (e.g., Newell & Simon, 1956) in the early attempts of computer simulation and artificial intelligence and also later work leading to the different versions of the adaptive control of thought (ACT) model (Anderson, 1983, 1990, 1996; Anderson & Bower, 1973; Anderson & Lebiere, 1998) already have shown that even solving difficult problems does not need a "ghost in the machine" (Ryle, 1949, p. 17) and can simply be achieved by applying rules and heuristics (Newell, Shaw, & Simon, 1958a, 1958b; Newell & Simon, 1961).

Discussion

From the first publication about the multicomponent working model by Baddeley and Hitch in 1974 until today, the model has proven to be a productive tool for new research, providing understanding of the operation of WM. All the components of the model have their function and are rooted in empirical findings, except for the central executive. Although evidence supports the involvement of executive processes, the central executive component is vaguely defined, with unlimited powers of control. As eloquently argued by Verbruggen et al. (2014), there is an urgent need to replace such explanations of control by a mechanistic account that refers to well-understood processes. In this vein, I propose in the present article that the central executive in the multicomponent WM model is replaced by a memory module that temporarily maintains task-execution-related information (task set) and that the control is performed by actions executed when the conditions match WM contents.

Given the description of the present modification of the model, a few critical questions deserve further attention. The first question is whether the proposed model is sufficient to replace the central executive. The second concerns the role of the proposed processes in an individual differences context. A third critical question concerns the validation of the adapted model.

Is the central executive made redundant?

The elaborative description of the model and its account of performance in executively demanding situations has shown that basic processes triggered by the congruency of WM contents and the condition part of rules stored in procedural LTM can account for selection of goal-directed action. The same mechanism also accounts for the occasional lapses that occur due to interference and noise in the WM representations. Actually, the processes involved in reproductive goal achievement cover all types of tasks that have been used in dual-task studies of the central executive. To substantiate this point, I consider the tasks used in such dual-task research one by one. In each case, the present account suffices to explain the observed dual-task interference effects.

Backward counting. Backward counting by 3 as in the early studies of decay in short-term memory (J. A. Brown, 1958; Peterson & Peterson, 1959) is one of the first tasks ever used to interfere with memory refreshment. Backward counting requires the repetitive application of a "minus 3" operation. This task can be performed by implementing the appropriate task set: subtracting 3 from the target number and then replacing the target number with the result of the subtraction. Application of condition-action rules in response to current WM contents suffices to perform this task repetitively.

Random generation of elements from a set. Another often-used task consists of random generation of elements from a set. For example, imagine repetitively throwing a die and announcing the upcoming number. Such tasks have been performed with letters or numbers (Baddeley, 1966; Robbins et al., 1996; Towse & Cheshire, 2007; Towse & Valentine, 1997), with selection of keys on a key pad (Baddeley, Emslie, Kolodny, & Duncan, 1998), and with time intervals (Vandierendonck, De Vooght, & Van der Goten, 1998a). All these variations of random generation involve simple control processes that mostly are triggered by instructions not to repeat the same item too often or not to produce familiar patterns or orders. Consequently, the task set specifies not only the requirement to retrieve elements or maybe strings of elements (Vandierendonck et al., 2012) but also the constraints that have been stressed in the instructions. All processes needed for executing such a task rely again on condition-action rules that are applied when they match the WM contents. The additional constraints stored with the task set activate rules that check for the presence of repetitions or familiarities.[7]

In random-interval repetition (Vandierendonck, De Vooght, & Van der Goten, 1998b), auditory stimuli (bleeps) are presented at random time intervals, and each detected bleep requires a fast detection response. The random variation of the time intervals discourages automatization of the detection response and again condition-action rules suffice to correctly execute the task.

Choice response. Most frequently, choice response tasks (Szmalec, Vandierendonck, & Kemps, 2005) are used in dual-task studies. Such tasks (e.g., parity judgment, location judgment, and so on) require selection of an appropriate response. Also the trails task (Lezak, 1983) has been used in some studies (Baddeley et al., 2001). The most difficult version of the task requires alternating between two well-known series (e.g., alternate between reciting days of the week and months of the year: Wednesday, March; Thursday, April; and so forth). Even though each series is well known, progress in each series must be remembered. Again, condition-action rules combined with the appropriate task set account for correct task performance.

Memorization. In a few studies, memorization has been used as a secondary task in recall (Depoorter & Vandierendonck, 2009). As explained previously, memorization requires a task set and is further governed by condition-action rules. When a memorization task is executed in the retention interval of another memorization task (with different contents), application of the condition-action rules matching WM contents completely accounts for controlled task execution.

In other words, existing dual-task research on the role of the central executive in WM has called on only reproductive-goal-achievement tasks, so there is no need to call on productive-goal-achievement actions. Although the present model accounts for productive-goal-achievement processes, in view of the kinds of tasks used to interfere with the central executive, one may ask whether productive-goal-achievement actions should also be part of the central executive. They are, no doubt, part of the cognitive repertoire, but is it necessary to assume that they are part of the executive control processes as needed in WM?

In an attempt to achieve a more restraining conceptualization of the central executive, Baddeley (1986) proposed that this agent corresponds to the supervisory attention system described by Norman and Shallice (1986).[8] Their model assumes two levels of control. As long as a well-trained skill is being executed, the system operates largely automatically; the occasional conflict is resolved semiautomatically on the basis of learned habits (contention scheduling). However, in novel situations or failures of the automatic conflict resolution, the supervisory attentional system comes into action. It intervenes in favor of one of the competing actions or can call on strategies for finding alternative solutions. The distinction between contention scheduling and supervisory attention seems to run parallel to the distinction made here between reproductive and productive goal achievement, although it is difficult to tell whether the two distinctions are completely equivalent. If this interpretation is correct, it follows that the present modeling can also account for actions subsumed by Norman and Shallice's (1986) supervisory attention system. The remaining question of whether it is necessary to assume that WM functioning calls on supervisory attention and problem solving requires further research.

In the present proposal, I clearly have gone beyond a simple fractionation of the central executive into a restricted set of smaller components. Instead, I have tried to identify the processes underlying executive control. However, because the proposal is based on ideas from research on task switching, some may argue that the present modeling is representative of only one executive function: (task-)set shifting. Indeed, in the classification of executive functions proposed by Miyake et al. (2000), the latent variable of set shifting corresponds to the common variance in a number of task-switching contexts. However, the common variance among three variations of task switching might involve more than simply set shifting. In fact, the latent variable is defined as the commonality in task demands of the various task-switching contexts involved; as documented in the present article, this involves much more than replacing one intention by another one. Similarly, the latent variables of memory updating and inhibition also are defined as the commonality in a series of task demands. For memory updating, it concerns demands common to a number of memory-updating procedures (see also Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011), and for inhibition, it concerns demands common to a number of situations in which an automatic response must be suppressed in favor of another response. Because the processes described in the present model include not only switching between tasks but also intentionally adapting memory contents (memory updating) and selecting some action sequences above other ones (selection and inhibition), it is clear that the model covers not only set shifting and task switching but also processes related to memory updating and inhibition.

Individual differences

Apart from being a central notion in experimental approaches to cognition, WM capacity—the number of chunks of information that can be kept active during performance of other tasks—is a property of the cognitive system that varies across persons. Complex-span tasks measure WM capacity in a standardized dual-task context; well-known examples are the reading span task (serial recall of words while processing sentences, Daneman & Carpenter, 1980), the counting span task (counting dots and remembering the results of a series of counts, Case, 1985), and the operation span task (serial recall of words while performing arithmetic operations, Turner & Engle, 1989). With the development of such complex WM span tasks, a correlational approach to WM was initiated. A popular and successful alternative to the experimental approach, the complex span measure is used in typical latent variable studies as well as in experimental designs in which one or more experimental variables are crossed with the contrast between subjects with a high and low complex-span performance. Important achievements of this approach include a large body of findings regarding the relation between WM capacity and other performance variables (for a review, see Barrett, Tugade, & Engle, 2004); robust results about the relationship between WM and fluid intelligence (Conway, Kane, & Engle, 2003; Unsworth & Engle, 2005); and new theoretical models of WM (e.g., Engle, Kane, & Tuholski, 1999).

Although the correlational approach to WM was not addressed in the present article, it is important to discuss the potential contribution of the proposed distributed control processes to individual difference approaches of WM. Just as the views on WM are rooted in experimental approaches, the correlational approach to WM sometimes calls on a control homunculus to account for individual differences in WM capacity. In the theoretical model of Engle, Kane, and Tuholski (1999), for example, the notion of executive attention plays a critical role. According to Unsworth, Schrock, and Engle (2004), executive attention plays a role in situations that require "inhibition of prepotent responses, error monitoring and correction, and decision making and planning" (p. 1302)—in other words, in situations that typically call on executive functions as defined by several other authors (e.g., Burgess, 1997; Miyake et al., 2000; Norman & Shallice, 1986). This list of situations also defines the scope of the supervisory attention model and the central executive in the multicomponent model of WM. This actually means that the labels *central executive* and *executive attention* refer to basically the same concept, and although executive attention has not been profiled as a homunculus, replacing this construct by distributed control processes is as valid as it is for the notion of central executive. However, because I did not refer explicitly to individual differences in this proposal, there is a need to specify how these control processes can account for individual differences in WM capacity.

In fact, the literature contains already a number of indications of how this can be achieved. For example, experiments with demanding tasks such as the Stroop task (naming the print color of nonmatching color words, Stroop, 1935) have shown that high-span individuals are better able than low-span individuals to keep the task goal active in WM (e.g., Kane & Engle, 2003; Kiefer, Ahlegian, & Spitzer, 2005; Long & Prat, 2002; Meier & Kane, 2013). This account is related to the notion of *goal neglect* (failure to attain the activated goal, Duncan et al., 2008) and corresponds to the present proposal that the task goal and, in particular, the task set are maintained in an active state in WM. It suggests that these processes are subject to individual differences and are part of what is measured by complex span tasks.

Similarly, several studies have shown that high-span persons are faster and more accurate than low-span persons in resolving conflicts between automatically triggered courses of action and intended actions; examples are the execution of controlled eye movements (e.g., Kane et al., 2001; Unsworth et al., 2004) and some visual attention tasks (see Vandierendonck, 2014, for an overview). Such conflict resolution processes typically occur in task-switching contexts, which were used for the present model. Again, the efficiency with which such processes can be performed seems to differ across persons with low and high WM capacity.

It is important to note that in these situations, there is a conflict or competition between an automatically triggered action (e.g., reading the color word in a Stroop task) and an intended action (naming the print color of the word). In some instances, the automatic action wins the competition; in other instances, the intended action does. Simply building up activation of the intended action at a faster rate or to a higher level, possibly jointly with lateral inhibition of the automatic action, suffices to let the intended action win this competition.

Some authors have assumed that active inhibition of the automatic action is needed in these and some other contexts. Although inhibition of a no-longer-needed task set is part of the present model, a general active inhibition process is not included and is not necessary. The model seems to do fine without direct inhibition (except for task sets). The present model assigns a key role to activation: WM contents have to be kept active and processes that boost activation of these contents achieve this goal. Activation of WM contents decays over time or can be inhibited indirectly by lateral inhibition. To directly inhibit (declarative) WM contents requires accessing these contents with the aim of decreasing their activation; however, accessing WM contents increases their activation. Hence, including active inhibition would require additional processes to make it work. Furthermore, the operationalization of the construct of inhibition in the model of Miyake et al. (2000) does not suggest that inhibition works in a direct way. In that model, the executive function of inhibition is a latent factor based on the common variance in three tasks: the (exogenous) anti-saccade task (executing an eye movement in the opposite direction of a peripheral cue), the Stroop task, and the stop-signal task (responding quickly to a target but withholding the response when a stop signal appears). All three tasks require the resolution of a conflict between two courses of action, so that it suffices to assume a competition between the activation of these two courses of action.[9]

The same processes that were proposed to account for executive control in general seem to be applicable in the context of the individual differences approach to WM. However, attention must also be paid to the observation that measures of WM capacity (complex span tasks) share an important amount of variance with fluid intelligence tasks such as the Raven's progressive matrices (Raven, Court, & Raven, 1977). As the relation to intelligence was not a theme in the present article, one may ask whether the model can account for such a relationship. This is largely an empirical question. It is difficult to see a direct link between the kind of processes needed in task-set control (reproductive goal achievement) and intelligence. However, in the context of problem solving (productive goal achievement), a relationship to intelligence seems evident. Because at present the importance of the contribution of each of these two sets of processes is not known, a substantiated answer can only be obtained on the basis of further empirical research.

Empirical support

Thus far in this discussion, I have addressed the claims that the present model can account for executive control processes in WM without invoking a homunculus and that the model can also account for individual differences in WM. Next, I address how empirical research can further substantiate the claims made in the model. One of the basic assumptions of the present model adaptation concerns the position that intentional memorizations as well as cognitive tasks require a task set for selection of the appropriate intentional actions. On the basis of this assumption, the model predicts the same effects of cognitive load in strictly timed dual-task designs that the TBRS model of Barrouillet and colleagues does (Barrouillet et al., 2007; Barrouillet et al., 2004; Barrouillet & Camos, 2010; Barrouillet, Portrat, & Camos, 2011; Portrat et al., 2008). Besides, because according to the present model, the cost of switching between the primary memorization task and the secondary task depends on the degree of overlap between the two task sets, an additional cost of switching may be expected. In particular, the greater the overlap of the two task sets, the larger the switch cost will be; as a result, there will be less time for memory refreshment and, consequently, a further impairment of recall.

Varying the requirements and demands of the memorization task can test the latter expectation. I argued that the overlap between a memorization task set and typical cognitive tasks (choice-response tasks) that are used in dual-task designs is rather low. By varying the demands of the memorization task, one also can vary the degree of overlap with secondary tasks, making it possible to compare a condition with low overlap to a condition with high overlap between memorization and secondary task. Such an increased overlap could be achieved by adding a task requirement to the memorization task. For example, instead of simple refreshment of the memory contents, the memory task could demand that after every task execution, the memoranda be changed on the basis of some memory-updating tasks (e.g., Oberauer, Suss, Schulze, Wilhelm, & Wittmann, 2000). With a larger overlap between memorization and task execution, switching between task execution and memorization would be expected to cost more time, which in a strictly timed design would be expected to result in poorer recall.

Another way to manipulate the overlap between memorization and secondary task concerns the inclusion of operations to be performed on the memoranda. To the extent that these operations overlap or are similar to actions required in the secondary tasks, the similarity between the task sets of memorization and secondary will be increased. One can think of conditions requiring a decision on each memorandum (cf. levels of processing methodology, Craik & Lockhart, 1972). Overlap between the memorization task and the secondary task then can vary with the degree of similarity between the required decision and the secondary task action. An example of such a task is one in which letters are presented to subjects for later recall but instead of recalling the letters that were presented, subjects are asked to perform an alphabet arithmetic task on each letter (e.g., "Replace each letter by the letter n positions later in the alphabet," Zbrodoff, 1999), then maintain the outcome of this operation, and recall it at the end of the task. If the secondary task calls for mental arithmetic, the overlap will be large, but if the secondary task requires another type of response, overlap will still be substantial but smaller. With increases in overlap, the chances of interference between the two task sets (of the memorization task and the secondary task) increase, making recovery or reactivation of the maintenance task set more difficult.

In contrast, if the operations to be performed during memorization do not overlap with the secondary task and are memorable, it may be expected that adding an additional task enhances memory, in line with typical levels-of-processing findings (Craik & Lockhart, 1972). This also applies when specific actions are applied to the memoranda, as in the so-called enactment effect: When during encoding, an action must be performed on each of a series of objects, this enactment results in improved recall compared with an equivalent time of encoding without the opportunity to manipulate the objects (Engelkamp, Zimmer, & Kurbjuweit, 1995; Engelkamp, Zimmer, Mohr, & Sellen, 1994; Mulligan & Hornstein, 2003; Steffens, Jelenec, Mecklenbra, & Thompson, 2006; Yang, Gathercole, & Allen, 2014). Furthermore, according to the present model, if enactment is studied with a secondary task that overlaps in task set with the memorization task, memory gain should be lowered in comparison to conditions with smaller degrees of overlap.

Another issue of interest is that the task set includes a parameter setting that determines the orientation of attention. Several studies have shown that performance on selective attention tasks is poorer when a memory load is present than when there is no memory load (e.g., Lavie, Hirst, de Fockert, & Viding, 2004). Similarly, subjects with a low WM capacity tend to perform more poorly on attention tasks than subjects with a high WM capacity (e.g., Kane & Engle, 2003; Kane, Poole, Tuholski, & Engle, 2006; Poole & Kane, 2009). For a review of the main findings regarding the interaction of selective attention tasks with WM and an explanation of the observed effects in terms of the model presented here, see Vandierendonck (2014). According to the present view, when a selective attention task is performed under memory load (i.e., during a memorization interval), secondary task performance may suffer to the extent that there are overlaps in the attentional settings of both task sets.

Another avenue for model testing consists of implementing a computational model based on the present assumptions and comparing performance of the model with human performance. A computational model based on assumptions that are quite close to the ones elaborated in the present article has been applied to a few experiments published in the literature (Vandierendonck, 2012). Performance of the model corresponded well to human performance. However, it is not easy to assess the extent to which the observed degree of correspondence to the data depends on the central assumptions made here. In each computational implementation, additional assumptions are needed to make the model run, so clearly more work along these lines is required. Nevertheless, together with other work (e.g., Kieras et al., 1999; Lovett et al., 1999; W. Schneider, 1999), this demonstrates that it is possible to account for executive control without invoking an autonomous agent such as a central executive.

Relation to other work

The version of a multicomponent WM model elaborated in the present article has not been developed in isolation of other views on WM. As was evident in the body of this article, the EM module resembles procedural working memory in Oberauer's (2009, 2010) WM model. The main differences between the present modeling and Oberauer's view were already clarified. In the present model, WM is not considered to be activated LTM but concerns a separate representation combining information from LTM with information from sensory input and mental states. Another difference concerns the architecture of the model: Instead of assuming a completely similar hierarchy of processes for activated declarative and procedural LTM as in the model of Oberauer, the present model assumes that the episodic buffer (similar to Oberauer's declarative WM) and EM (similar to Oberauer's procedural WM) not only have different contents but also operate in a manner that is adapted for the type of content.

The model also shows important similarities to the views developed by Barrouillet and colleagues (2004, 2011). Their TBRS model is based on the assumption that there is a structural bottleneck that prohibits the central attentional resource to be allocated to more than one activity at a time, so the usage of time is crucial. In the present model, usage of time is similarly critical, not because of a basic assumption about serial processing but because the model assumes that goal-directed activities have representations in WM; these representations are the conditions that activate the procedural rules, so that only the rules that match the representations that are relevant to the currently dominant task set will be triggered at any time. This difference between the present model and the TBRS model pertains to the hypothesized underlying processes and is the basis for variance of task-set overlap between memorization and secondary tasks. Such an overlap can lead to additional impairment of recall if the cost of switching between the two tasks is too large. Apart from that, the present model basically makes the same predictions as the TBRS model, because the present model also assumes decay of WM contents that are not refreshed or rehearsed.

Finally, the present model shares many similarities with models developed as follow-ups to early computer simulation and artificial intelligence projects, the best known of which probably are the ACT model and its variants (Anderson, 1983, 1996; Anderson & Lebiere, 1998; Lovett et al., 1999). Using similar approaches, researchers developed several models of general cognitive function and WM, such as the executive process-interactive control (EPIC) model (Kieras et al., 1999; Meyer & Kieras, 1997a, 1997b), Soar cognitive architecture (Young & Lewis, 1999), and others (W. Schneider, 1999). Also a few specifically designed models were proposed as alternatives to traditional WM views (Barnard, 1999; O'Reilly, Braver, & Cohen, 1999).

In view of all these efforts, one may ask whether these modeling efforts have not solved the homunculus problem already. Indeed, the present proposal bears many similarities to production models such as adaptive control of thought-rational (ACT-R) and EPIC. In fact, these models are powerful computational devices with the potential to include executive control processes in the more specific models developed with these tools. An ACT-R model of WM has been published (Lovett et al., 1999). In this model, WM is the activated part of LTM, and although the model does account for dual-tasking effects, it does not include control mechanisms to link WM to higher cognitive processes. The WM modeling within the EPIC framework (Kieras et al., 1999) comes much closer to the present claim that it is possible to replace the central executive by specific control processes embedded in production rules by giving an account of executive processes involved in verbal WM. In the present model, I extend this previous work by trying to account for the complete scope of a central executive agent in WM.

Conclusion

The model presented here—an adaptation of the multi-component WM model—eliminates the central executive as a homunculus by replacing it with a passive store, a procedural LTM network, and an engine governing their interaction. The passive store contains information relevant to task execution—the task set. These contents and those of the other WM components trigger matching rules in the procedural LTM network, which results in automatic application of the most relevant matching rules to change the WM contents in any of its storage modules (phonological loop, visuospatial sketch pad, episodic buffer, and EM) or to initiate a motor action. This model accounts for both productive and reproductive goal achievement.

Declaration of Conflicting Interests

The author declared no conflicts of interest with respect to the authorship or the publication of this article.

Notes

1. It is indeed the first model explicitly proposed to account for WM, even though Miller, Galanter, and Pribram (1960) were probably the first to use the term *working memory*, and Atkinson and Shiffrin (1971) were the first to indicate that short-term memory could be referred to as working memory because of the many control processes involved (coding, chunking, and so on).
2. Note, however, that although the presence of a verbal goal may be useful in task switching, it does not seem to be sufficient for goal attainment, as the verbal goal is merely a reminder of the current goal state.
3. Note that because the phonological loop and the episodic buffer have different functions, it is perfectly possible for some piece of information to be maintained in both modules.
4. Like the other parameter settings of the active task set, the specification of the orientation of attention is needed for the processes related to task execution. If this parameter specifies that attention be focused on the central area of the visual field, this implies that stimuli occurring in that part of the field will be processed and encoded within the episodic buffer, but stimuli outside this area are less likely to be processed. On the contrary, when the parameter indicates that attention is spread over the major part of the visual field, all stimuli within that part of the field will be processed. There is no homunculus to make any decisions about attentional orientation; instead the attentional orientation is installed with the task set on the basis of information retrieved from LTM.
5. Because the information in this and following examples is in the verbal modality, the phonological loop may be used to maintain this information. However, as in the present example binding is required, it is necessary to assume that the episodic buffer is involved.
6. This can occur after an error has been committed by applying a rule that changes the response threshold.
7. This account of the control processes required in random generation suggests that random generation is not a difficult task. However, most people who have tried to generate random events know from experience that random generation is in fact quite difficult. This subjective difficulty stems from the fact that random generation (i.e., producing a series of events such that these events are equiprobable and independent) is not part of our behavioral repertoire. It is next to impossible for humans to select a series of events that obeys the statistical criterion of stochastic independence. Even though every generated sequence, whatever its statistical properties, can be produced by a purely random process, most people will have doubts about the random qualities of the series because they are aware of the many times corrections have been made to the spontaneously generated events. Moreover, spontaneously produced sequences cannot be trusted to be random either because of the occurrence of priming and retrieval of known sequences from LTM.
8. At the time of this writing, this position is still maintained by Alan Baddeley as he confirmed in personal communications I had with him at the occasion of the International Conference on Working Memory in Cambridge (July 2014) and the Seventh European Working Memory Symposium (EWOMS 7) conference in Edinburgh, Scotland (September 2014).

9. Note that this competition also applies for the stop-signal task. Accounts of the stop-signal task assume a competition between two processes: execution of the response required for the target and a process that blocks responding (Logan & Cowan, 1984).

References

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General*, *135*, 298–313. doi:10.1037/0096-3445.135.2.298

Allen, R. J., Hitch, G. J., Mate, J., & Baddeley, A. D. (2012). Feature binding and attention in working memory: A resolution of previous contradictory findings. *Quarterly Journal of Experimental Psychology*, *65*, 2369–2383. doi:10.1080/17470218.2012.687384

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting attentional set: Exploring the dynamic control of tasks. In C. Umiltá & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421–452). Cambridge, MA: MIT Press.

Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University Press.

Anderson, J. R. (1990). *The adaptive character of thought*. Hillsdale, NJ: Erlbaum.

Anderson, J. R. (1996). ACT: A simple theory of complex cognition. *American Psychologist*, *51*, 355–365.

Anderson, J. R., & Bower, G. H. (1973). *Human associative memory*. Washington, DC: Winston.

Anderson, J. R., Kline, P. J., & Beasley, C. M., Jr. (1979). A general learning theory and its application to schema abstraction. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 13, pp. 277–318). New York, NY: Academic Press.

Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought*. New York, NY: Erlbaum.

Arrington, C. M. (2008). The effect of stimulus availability on task choice in voluntary task switching. *Memory & Cognition*, *36*, 991–997. doi:10.3758/mc.36.5.991

Arrington, C. M., & Logan, G. D. (2004). The cost of a voluntary task switch. *Psychological Science*, *15*, 610–615. doi:10.1111/j.0956-7976.2004.00728.x

Arrington, C. M., & Logan, G. D. (2005). Voluntary task switching: Chasing the elusive homunculus. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 683–702. doi:10.1037/0278-7393.31.4.683

Arrington, C. M., & Rhodes, K. M. (2010). Perceptual asymmetries influence task choice: The effect of lateralised presentation of hierarchical stimuli. *Laterality*, *15*, 501–513. doi:10.1080/13576500902984695

Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American*, *225*, 82–90.

Baddeley, A. D. (1966). The capacity for generating information by randomization. *Quarterly Journal of Experimental Psychology*, *18*, 119–129.

Baddeley, A. D. (1966). The capacity for generating information by randomization. *Quarterly Journal of Experimental Psychology*, *18*, 119–129.

Baddeley, A. D. (1986). *Working memory*. Oxford, England: Oxford University Press.

Baddeley, A. D. (1996a). Exploring the central executive. *Quarterly Journal of Experimental Psychology*, *49A*, 5–28.

Baddeley, A. D. (1996b). The fractionation of working memory. *Proceedings of the National Academy of Sciences, USA*, *93*, 13468–13472.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*, 417–423. doi:10.1016/S1364-6613(00)01538-2[

Baddeley, A. D., Allen, R. J., & Hitch, G. J. (2010). Investigating the episodic buffer. *Psychologica Belgica*, *50*, 223–243.

Baddeley, A. D., Chincotta, D., & Adlam, A. (2001). Working memory and the control of action: Evidence from task switching. *Journal of Experimental Psychology: General*, *130*, 641–657. doi:10.1037//0096-3445.130.4.641

Baddeley, A. D., Emslie, H., Kolodny, J., & Duncan, J. (1998). Random generation and the executive control of working memory. *Quarterly Journal of Experimental Psychology*, *51A*, 819–852. doi:10.1080/027249898391413

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47–89). New York, NY: Academic Press.

Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language*, *61*, 438–456. doi:10.1016/j.jml.2009.05.004

Baddeley, A. D., Lewis, V. J., & Vallar, G. (1984). Exploring the articulatory loop. *Quarterly Journal of Experimental Psychology*, *36A*, 233–252.

Baddeley, A. D., Logie, R. H., Bressi, S., Della Sala, S., & Spinnler, H. (1986). Dementia and working memory. *Quarterly Journal of Experimental Psychology, 38A*, 603–618.

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 28–61). Cambridge, England: Cambridge University Press.

Barnard, P. J. (1999). Interacting cognitive systems: Modeling working memory phenomena within a multiprocessor architecture. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 298–339). Cambridge, England: Cambridge University Press.

Barrett, L. F., Tugade, M. M., & Engle, R. W. (2004). Individual differences in working memory capacity and dual-process theories of the mind. *Psychological Bulletin*, *130*, 553–573. doi:10.1037/0033-2909.130.4.553

Barrouillet, P., Bemardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 570–585. doi:10.1037/0278-7393.33.3.570

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*, 83–100. doi:10.1037/0096-3445.133.1.83

Barrouillet, P., & Camos, V. (2010). Working memory and executive control: A Time-Based Resource-Sharing account. *Psychologica Belgica*, *50*, 353–382.

Barrouillet, P., Lépine, R., & Camos, V. (2008). Is the influence of working memory capacity on high-level cognition mediated by complexity or resource-dependent elementary processes? *Psychonomic Bulletin & Review*, *15*, 528–534. doi:10.3758/pbr.15.3.528

Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working memory. *Psychological Review*, *118*, 175–192. doi:10.1037/a0022324

Barrouillet, P., Portrat, S., Vergauwe, E., Diependaele, K., & Camos, V. (2011). Further evidence for temporal decay in working memory: Reply to Lewandowsky and Oberauer (2009). *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*, 1302–1317. doi:10.1037/a0022933

Brown, J. A. (1958). Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology*, *10*, 10–22.

Brown, J. W., Reynolds, J. R., & Braver, T. S. (2007). A computational model of fractionated conflict-control mechanisms in task-switching. *Cognitive Psychology*, *55*, 37–85. doi:10.1016/j.cogpsych.2006.09.005

Bryck, R. L., & Mayr, U. (2005). On the role of verbalization during task set selection: Switching or serial order control? *Memory & Cognition*, *33*, 611–623.

Burgess, P. W. (1997). Theory and methodology in executive function research. In P. Rabbitt (Ed.), *Methodology of frontal and executive function* (pp. 81–116). Hove, England: Psychology Press.

Butler, K. M., Arrington, C. M., & Weywadt, C. (2011). Working memory capacity modulates task performance but has little influence on task choice. *Memory & Cognition*, *39*, 708–724. doi:10.3758/s13421-010-0055-y

Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*, *61*, 457–469. doi:10.1016/j.jml.2009.06.002

Camos, V., Mora, G., & Barrouillet, P. (2013). Phonological similarity effect in complex span task. *Quarterly Journal of Experimental Psychology*, *66*, 1927–1950. doi:10.1080/17470218.2013.768275

Camos, V., Mora, G., & Oberauer, K. (2011). Adaptive choice between articulatory rehearsal and attentional refreshing in verbal working memory. *Memory & Cognition*, *39*, 231–244. doi:10.3758/s13421-010-0011-x

Case, R. (1985). *Intellectual development: Birth to adulthood*. New York, NY: Academic Press.

Case, R., Kurland, D. M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term-memory span. *Journal of Experimental Child Psychology*, *33*, 386–404.

Cohen-Kdoshay, O., & Meiran, N. (2007). The representation of instructions in working memory leads to autonomous response activation: Evidence from the first trials in the flanker paradigm. *Quarterly Journal of Experimental Psychology*, *60*, 1140–1154. doi:10.1080/17470210600896674

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*, 547–552. doi:10.1016/j.tics.2003.10.005

Cowan, N. (1999). An embedded-process model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). Cambridge, England: Cambridge University Press.

Cowan, N. (2005). *Working memory capacity*. Hove, England: Psychology Press.

Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*, 671–684.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory. *Journal of Verbal Learning and Verbal Behavior*, *19*, 450–466. doi:10.1016/S0022-5371(80)90312-6

de Groot, A. D. (1965). *Thought and choice in chess*. The Hague, The Netherlands: Mouton.

Demanet, J., Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2010). Voluntary task switching under load: Contribution of top-down and bottom-up factors in goal-directed behavior. *Psychonomic Bulletin & Review*, *17*, 387–393. doi:10.3758/PBR.17.3.387

Depoorter, A., & Vandierendonck, A. (2009). Evidence for modality-independent order coding in working memory. *Quarterly Journal of Experimental Psychology*, *62*, 531–549. doi:10.1080/17470210801995002

DeStefano, D., & LeFevre, J.-A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology*, *16*, 353–386. doi:10.1080/09541440244000328

Duncan, J., Parr, A., Woolgar, A., Thompson, R., Bright, P., Cox, S., . . . Nimmo-Smith, I. (2008). Goal neglect and Spearman's g: Competing parts of a complex task. *Journal of Experimental Psychology: General*, *137*, 131–148. doi:10.1037/0096-3445.137.1.131

Emerson, M. J., & Miyake, A. (2003). The role of inner speech in task switching: A dual-task investigation. *Journal of Memory and Language*, *48*, 148–168. doi:10.1016/S0749-596X(02)00511-9

Engelkamp, J., Zimmer, H. D., & Kurbjuweit, A. (1995). Verb frequency and enactment in implicit and explicit memory. *Psychological Research*, *57*, 242–249. doi:10.1007/bf00431285

Engelkamp, J., Zimmer, H. D., Mohr, G., & Sellen, O. (1994). Memory of self-performed tasks: Self-performing during recognition. *Memory & Cognition*, *22*, 34–39. doi:10.3758/bf03202759

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). Cambridge, England: Cambridge University Press.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. (1999). Working memory, short term memory, and general fluid intelligence: A latent variable approach. *Journal of Experimental Psychology: General*, *128*, 309–311.

Eysenck, M. W., & Calvo, M. G. (1992). Anxiety and performance: The processing efficiency theory. *Cognition & Emotion*, *6*, 409–434. doi:10.1080/02699939208409696

Gilbert, S. J., & Shallice, T. (2002). Task switching: A PDP model. *Cognitive Psychology*, *44*, 297–337. doi:10.1006/cogp.2001.0770

Gopher, D., Armony, L., & Greenshpan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology: General*, *129*, 308–339. doi:10.1037//0096-3445.129.3.308

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task set switching. In S. Monsell & J. S. Driver (Eds.), *Control of cognitive processes: Attention and performance XVIII* (pp. 331–355). Cambridge, MA: MIT Press.

Hitch, G. (1978). The role of short-term working memory in mental arithmetic. *Cognitive Psychology*, *10*, 302–323.

Holyoak, K. J., Koh, K., & Nisbett, R. E. (1989). A theory of conditioning: Inductive learning with rule-based default-hierarchies. *Psychological Review*, *96*, 315–340.

Hsieh, S. (2002). Task shifting in dual-task settings. *Perceptual & Motor Skills*, *94*, 407–414.

Hughes, M. M., Linck, J. A., Bowles, A. R., Koeth, J. T., & Bunting, M. F. (2014). Alternatives to switch-cost scoring in the task-switching paradigm: Their reliability and increased validity. *Behavior Research Methods*, *46*, 702–721. doi:10.3758/s13428-013-0411-5

Hunt, A. R., & Kingstone, A. (2004). Multisensory executive functioning. *Brain and Cognition*, *55*, 325–327. doi:10.1016/j.bandc.2004.02.072

Imbo, I., & Vandierendonck, A. (2007). The role of phonological and executive working memory resources in simple arithmetic strategies. *European Journal of Cognitive Psychology*, *19*, 910–933. doi:10.1080/09541440601051571

Imbo, I., Vandierendonck, A., & De Rammelaere, S. (2007). The role of working memory in the carry operation of mental arithmetic: Number and value of the carry. *Quarterly Journal of Experimental Psychology*, *60*, 708–731. doi:10.1080/17470210600762447

Just, M. A., & Carpenter, G. A. (1992). A capacity theory of comprehension: Individual-differences in working memory. *Psychological Review*, *99*, 122–149.

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*, 169–183. doi:10.1037/0096-3445.130.2.169

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. In A. R. A. Conway, C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse (Eds.), *Variations in working memory* (pp. 21–48). New York, NY: Oxford University Press.

Kane, M. J., & Engle, R. W. (2003). Working-memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. *Journal of Experimental Psychology: General*, *132*, 47–70. doi:10.1037/0096-3445.132.1.47

Kane, M. J., Poole, B. J., Tuholski, S. W., & Engle, R. W. (2006). Working memory capacity and the top-down control of visual search: Exploring the boundaries of "executive attention." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*, 749–777. doi:10.1037/0278-7393.32.4.749

Kessler, Y., & Meiran, N. (2010). The reaction-time task-rule congruency effect is not affected by working memory load: Further support for the activated long-term memory hypothesis. *Psychological Research/Psychologische Forschung*, *74*, 388–399. doi:10.1007/s00426-009-0261-z

Kiefer, M., Ahlegian, M., & Spitzer, M. (2005). Working memory capacity, indirect semantic priming, and Stroop interference: Pattern of interindividual prefrontal performance differences in healthy volunteers. *Neuropsychology*, *19*, 332–344. doi:10.1037/0894-4105.19.3.332

Kieras, D. E., Meyer, D. E., Mueller, S., & Seymour, T. (1999). Insights into working memory from the perspective of the EPIC architecture for modelling skilled perceptual-motor and cognitive human performance. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 183–223). Cambridge, England: Cambridge University Press.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—A review. *Psychological Bulletin*, *136*, 849–874. doi:10.1037/a0019842

Kiesel, A., Wendt, M., & Peters, A. (2007). Task switching: On the origin of response congruency effects. *Psychological Research/Psychologische Forschung*, *71*, 117–125. doi:10.1007/s00426-005-0004-8

Klauer, K. C., Stegmaier, R., & Meiser, T. (1997). Working memory involvement in propositional and spatial reasoning. *Thinking & Reasoning*, *3*, 9–47. doi:10.1080/135467897394419

Koch, I., Gade, M., & Philipp, A. M. (2004). Inhibition of response mode in task switching. *Experimental Psychology*, *51*, 52–58. doi:10.1027//1618-3169.51.1.52

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*, 339–354. doi:10.1037/0096-3445.133.3.339

Lezak, M. D. (1983). *Neuropsychological assessment*. New York, NY: Oxford University Press.

Liefooghe, B., Barrouillet, P., Vandierendonck, A., & Camos, V. (2008). Working memory costs of task switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 478–494. doi:10.1037/0278-7393.34.3.478

Liefooghe, B., De Houwer, J., & Wenke, D. (2013). Instruction-based response activation depends on task preparation. *Psychonomic Bulletin & Review*, *20*, 481–487. doi:10.3758/s13423-013-0374-7

Liefooghe, B., Demanet, J., & Vandierendonck, A. (2009). Is advance reconfiguration in voluntary task switching affected by the design employed? *Quarterly Journal of Experimental Psychology*, *62*, 850–857. doi:10.1080/17470210802570994

Liefooghe, B., Vandierendonck, A., Muyllaert, I., Verbruggen, F., & Vanneste, W. (2005). The phonological loop in task alternation and task repetition. *Memory*, *13*, 550–560. doi:10.1080/09658210444000250

Lien, M. C., & Ruthruff, E. (2004). Task switching in a hierarchical task structure: Evidence for the fragility of the task repetition benefit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 697–713. doi:10.1037/0278-7393.30.3.697

Logan, G. D. (2003). Executive control of thought and action: In search of the wild homunculus. *Current Directions in Psychological Science*, *12*, 45–48.

Logan, G. D. (2004). Working memory, task switching, and executive control in the task span procedure. *Journal of Experimental Psychology: General*, *133*, 218–236.

Logan, G. D. (2006). Out with the old, in with the new: More valid measures of switch cost and retrieval time in the task span procedure. *Psychonomic Bulletin & Review*, *13*, 139–144.

Logan, G. D. (2007). What it costs to implement a plan: Plan-level and task-level contributions to switch costs. *Memory & Cognition*, *35*, 591–602.

Logan, G. D., & Bundesen, C. (2003). Clever homunculus: Is there an endogenous act of control in the explicit task-cuing procedure? *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 575–599. doi:10.1037/0096-1523.29.3.575

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*, 295–327.

Logan, G. D., & Gordon, R. D. (2001). Executive control of attention in dual-task situations. *Psychological Review*, *108*, 393–434.

Logie, R. H. (1995). *Visuo-spatial working memory*. Hillsdale, NJ: Erlbaum.

Long, D. L., & Prat, C. S. (2002). Working memory and Stroop interference: An individual differences investigation. *Memory & Cognition*, *30*, 294–301. doi:10.3758/bf03195290

Lovett, M. C., Reder, L. M., & Lebiere, C. (1999). Modeling working memory in a unified architecture. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 135–182). Cambridge, England: Cambridge University Press.

Mayr, U., & Bell, T. (2006). On how to be unpredictable: Evidence from the voluntary task-switching paradigm. *Psychological Science*, *17*, 774–780. doi:10.1111/j.1467-9280.2006.01781.x

Mayr, U., & Bryck, R. L. (2005). Sticky rules: Integration between abstract rules and specific actions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*, 337–350.

Meier, M. E., & Kane, M. J. (2013). Working memory capacity and Stroop interference: Global versus local indices of executive control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 748–759. doi:10.1037/a0029200

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 1423–1442. doi:10.1037/0278-7393.22.6.1423

Meiran, N. (2000). Modeling cognitive control in task-switching. *Psychological Research/Psychologische Forschung*, *63*, 234–249. doi:10.1007/s004269900004

Meyer, D. E., & Kieras, D. E. (1997a). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, *104*, 3–65.

Meyer, D. E., & Kieras, D. E. (1997b). A computational theory of executive cognitive processes and multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, *104*, 749–791.

Miller, G. A., Galanter, E., & Pribram, K. H. (1960). *Plans and the structure of behavior*. New York, NY: Henry Holt.

Miyake, A., Emerson, M. J., Padilla, F., & Ahn, J. C. (2004). Inner speech as a retrieval aid for task goals: The effects of cue type and articulatory suppression in the random task cuing paradigm. *Acta Psychologica*, *115*, 123–142. doi:10.1016/j.actpsy.2003.12.004

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49–100. doi:10.1006/cogp.1999.0734

Monsell, S. (1996). Control of mental processes. In V. Bruce (Ed.), *Unsolved mysteries of the mind* (pp. 93–148). Hove, England: Erlbaum.

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*, 134–140. doi:10.1016/s1364(03)00028-7

Monsell, S., & Mizon, G. A. (2006). Can the task-cuing paradigm measure an endogenous task-set reconfiguration process? *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 493–516. doi:10.1037/0096-1523.32.3.493

Mora, G., & Camos, V. (2013). Two systems of maintenance in verbal working memory: Evidence from the word length effect. *PLoS ONE*, *8*(7), e70026. doi:10.1371/journal.pone.0070026

Mulligan, N. W., & Hornstein, S. L. (2003). Memory for actions: Self-performed tasks and the reenactment effect. *Memory & Cognition*, *31*, 412–421. doi:10.3758/bf03194399

Murray, M. M., De Santis, L., Thut, G., & Wylie, G. R. (2009). The costs of crossing paths and switching tasks between audition and vision. *Brain and Cognition*, *69*, 47–55. doi:10.1016/j.bandc.2008.05.004

Neumann, O. (1984). Automatic processing: A review of recent findings and a plea for an old theory. In W. Prinz & A. Sanders (Eds.), *Cognition and motor processes* (pp. 245–293). Berlin, Germany: Springer.

Newell, A. (1981). Reasoning, problem solving and decision processes: The problem space as a fundamental category. In R. Nickerson (Ed.), *Attention and performance VIII* (pp. 693–718). Hillsdale, NJ: Erlbaum.

Newell, A., & Shaw, J. C. (1959). Report on a general problem-solving program. *Communications of the ACM*, *2*(7), 18–19.

Newell, A., Shaw, J. C., & Simon, H. A. (1958a). Chess-playing programs and the problem of complexity. *IBM Journal of Research and Development*, *2*, 320–335.

Newell, A., Shaw, J. C., & Simon, H. A. (1958b). Elements of a theory of human problem-solving. *Psychological Review*, *65*, 151–166. doi:10.1037/h0048495

Newell, A., & Simon, H. A. (1956). The logic theory machine: A complex information-processing system. *IRE Transactions on Information Theory*, *2*(3), 61–79. doi:10.1109/tit.1956.1056797

Newell, A., & Simon, H. A. (1961, December 22). Computer simulation of human thinking: A theory of problem solving expressed as a computer program permits simulation of thinking processes. *Science*, *134*, 2011–2017. doi:10.1126/science.134.3495.2011

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R. J. Davidson,

G. E. Schwarts, & D. Shapiro (Eds.), *Consciousness and self-regulation* (Vol. 4, pp. 1–18). New York, NY: Plenum Press.

Oberauer, K. (2009). Design for a working memory. In B. H. Ross (Ed.), *Psychology of learning and motivation: Advances in research and theory* (Vol. 51, pp. 45–100). San Diego, CA: Elsevier Academic Press.

Oberauer, K. (2010). Declarative and procedural working memory: Common principles, common capacity limits? *Psychologica Belgica*, *50*, 277–308.

Oberauer, K., & Lewandowsky, S. (2011). Modeling working memory: A computational implementation of the Time-Based Resource-Sharing theory. *Psychonomic Bulletin & Review*, *18*, 10–45. doi:10.3758/s13423-010-0020-6

Oberauer, K., Suss, H. M., Schulze, R., Wilhelm, O., & Wittmann, W. W. (2000). Working memory capacity: Facets of a cognitive ability construct. *Personality and Individual Differences*, *29*, 1017–1045. doi:10.1016/s0191-8869(99)00251-2

Oberauer, K., Süss, H. M., Wilhelm, O., & Wittman, W. W. (2003). The multiple faces of working memory: Storage, processing, supervision, and coordination. *Intelligence*, *31*, 167–193. doi:10.1016/s0160-2896(02)00115-0

O'Reilly, R. C., Braver, T. S., & Cohen, J. D. (1999). A biologically based computational model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 375–411). Cambridge, England: Cambridge University Press.

Pashler, H., & Baylis, G. (1991a). Procedural learning: 1. Locus of practice effects in speeded choice tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*, 20–32. doi:10.1037/0278-7393.17.1.20

Pashler, H., & Baylis, G. (1991b). Procedural learning: 2. Intertrial repetition effects in speeded choice tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*, 33–48. doi:10.1037/0278-7393.17.1.33

Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of Child Psychology and Psychiatry*, *37*, 51–87. doi:10.1111/j.1469-7610.1996.tb01380.x

Peterson, L. R., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, *58*, 193–198.

Philipp, A. M., & Koch, I. (2005). Switching of response modalities. *Quarterly Journal of Experimental Psychology*, *58A*, 1325–1338. doi:10.1080/02724980443000656

Poole, B. J., & Kane, M. J. (2009). Working-memory capacity predicts the executive control of visual search among distractors: The influences of sustained and selective attention. *Quarterly Journal of Experimental Psychology*, *62*, 1430–1454. doi:10.1080/17470210802479329

Portrat, S., Barrouillet, P., & Camos, V. (2008). Time-related decay or interference-based forgetting in working memory? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 1561–1564. doi:10.1037/a0013356

Raven, J. C., Court, J. H., & Raven, J. (1977). *Standard progressive matrices*. London, United Kingdom: H. K. Lewis & Co.

Robbins, T., Anderson, E., Barker, D., Bradley, A., Fearneyhough, C., Henson, R., . . . Baddeley, A. (1996). Working memory in chess. *Memory & Cognition*, *24*, 83–93.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124*, 207–231. doi:10.1037/0096-3445.124.2.207

Rotzer, S., Loenneker, T., Kucian, K., Martin, E., Klaver, P., & von Aster, M. (2009). Dysfunctional neural network of spatial working memory contributes to developmental dyscalculia. *Neuropsychologia*, *47*, 2859–2865. doi:10.1016/j.neuropsychologia.2009.06.009

Ryle, G. (1949). *The concept of mind*. London, England: Hutchinson House.

Saeki, E., & Saito, S. (2004a). Effect of articulatory suppression on task-switching performance: Implications for models of working memory. *Memory*, *12*, 257–271. doi:10.1080/09658210244000649

Saeki, E., & Saito, S. (2004b). The role of the phonological loop in task switching performance: The effect of articulatory suppression in the alternating runs paradigm. *Psychologia*, *47*(1), 35–43.

Saeki, E., & Saito, S. (2009). Verbal representation in task order control: An examination with transition and task cues in random task switching. *Memory & Cognition*, *37*, 1040–1050. doi:10.3758/mc.37.7.1040

Saeki, E., & Saito, S. (2012). Differential effects of articulatory suppression on cue-switch and task-switch trials in random task cueing with 2:1 mapping. *Quarterly Journal of Experimental Psychology*, *65*, 1599–1614. doi:10.1080/17470218.2012.659191

Saeki, E., Saito, S., & Kawaguchi, J. (2006). Effects of response-stimulus interval manipulation and articulatory suppression on task switching. *Memory*, *14*, 965–976. doi:10.1080/09658210601008973

Schneider, D. W., & Logan, G. D. (2006). Hierarchical control of cognitive processes: Switching tasks in sequences. *Journal of Experimental Psychology: General*, *135*, 623–640. doi:10.1037/0096-3445.135.4.623

Schneider, W. (1999). Working memory in a multilevel hybrid connectionist control architecture (CAP2). In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 340–374). Cambridge, England: Cambridge University Press.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic information processing. I. Detection, search, and attention. *Psychological Review*, *84*, 1–66. doi:10.1037/0033-295X.84.1.1

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 92–105.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing. II. Perceptual learning, autonomic attending, and a general theory. *Psychological Review*, *84*, 127–190. doi:10.1037//0033-295X.84.2.127

Steffens, M. C., Jelenec, P., Mecklenbra, S., & Thompson, E. M. (2006). Decomposing retrieval and integration in memory for actions: A multinomial modeling approach. *Quarterly Journal of Experimental Psychology*, *59*, 557–576. doi:10.1080/02724980443000764

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*, 643–662.

Szmalec, A., Vandierendonck, A., & Kemps, E. (2005). Response selection involves executive control: Evidence from the selective interference paradigm. *Memory & Cognition*, *33*, 531–541. doi:10.3758/bf03193069

Szmalec, A., Verbruggen, F., Vandierendonck, A., & Kemps, E. (2011). Control of interference during working memory updating. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 137–151. doi:10.1037/a0020365

Towse, J. N., & Cheshire, A. (2007). Random number generation and working memory. *European Journal of Cognitive Psychology*, *19*, 374–394.

Towse, J. N., & Valentine, J. D. (1997). Random generation of numbers: A search for underlying processes. *European Journal of Cognitive Psychology*, *9*, 381–400.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*, 127–154.

Unsworth, N., & Engle, R. W. (2005). Working memory capacity and fluid abilities: Examining the correlation between Operation Span and Raven. *Intelligence*, *33*, 67–81. doi:10.1016/j.intell.2004.08.003

Unsworth, N., & McMillan, B. D. (2013). Mind wandering and reading comprehension: Examining the roles of working memory capacity, interest, motivation, and topic experience. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 832–842. doi:10.1037/a0029669

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 1302–1321. doi:10.1037/0278-7393.30.6.1302

Vandierendonck, A. (1995). A parallel rule activation and rule synthesis model for generalization in category learning. *Psychonomic Bulletin & Review*, *2*, 442–459.

Vandierendonck, A. (2012). Role of working memory in task switching. *Psychologica Belgica*, *52*, 229–253. doi:10.5334/pb-52-2-3-229

Vandierendonck, A. (2014, August 8). Symbiosis of executive and selective attention in working memory. *Frontiers in Human Neuroscience*, *8*. Article 588. doi:10.3389/fnhum.2014.00588

Vandierendonck, A., Demanet, J., Liefooghe, B., & Verbruggen, F. (2012). A chain-retrieval model for voluntary task switching. *Cognitive Psychology*, *65*, 241–283. doi:10.1016/j.cogpsych.2012.04.003

Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998a). Does random time interval generation interfere with working memory executive functions? *European Journal of Cognitive Psychology*, *10*, 413–442.

Vandierendonck, A., De Vooght, G., & Van der Goten, K. (1998b). Interfering with the central executive by means of a random interval repetition task. *Quarterly Journal of Experimental Psychology, 51A*, 197–218.

Vandierendonck, A., Liefooghe, B., & Verbruggen, G. (2010). Task switching: Interplay of reconfiguration and interference control. *Psychological Bulletin*, *136*, 601–626. doi:10.1037/a0019791

Vandierendonck, A., Szmalec, A., Deschuyteneer, M., & Depoorter, A. (2007). Towards a multicomponential view of executive control. The case of response selection. In N. Osaka & R. Logie (Eds.), *Working memory: Behavioural and neural correlates* (pp. 247–259). Oxford, England: Oxford University Press.

Van't Wout, F., Lavric, A., & Monsell, S. (2013). Are stimulus-response rules represented phonologically for task-set preparation and maintenance? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 1538–1551. doi:10.1037/a0031672

Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2006). Selective stopping in task switching: The role of response selection and response execution. *Experimental Psychology*, *53*, 48–57. doi:10.1027/1618-3169.53.1.48

Verbruggen, F., McLaren, I. P. L., & Chambers, C. D. (2014). Banishing the control homunculi in studies of action control and behavior change. *Perspectives on Psychological Science*, *9*, 497–524. doi:10.1177/1745691614526414

Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource? *Psychological Science*, *21*, 384–390. doi:10.1177/0956797610361340

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus—Task bindings in task-shift costs. *Cognitive Psychology*, *46*, 361–413. doi:10.1016/s0010-0285(02)00520-0

Waszak, F., Hommel, B., & Allport, A. (2004). Semantic generalization of stimulus-task bindings. *Psychonomic Bulletin & Review*, *11*, 1027–1033.

Waszak, F., Hommel, B., & Allport, A. (2005). Interaction of task readiness and automatic retrieval in task switching: Negative priming and competitor priming. *Memory & Cognition*, *33*, 595–610.

Weaver, S. M., & Arrington, C. M. (2010). What's on your mind: The influence of the contents of working memory on choice. *Quarterly Journal of Experimental Psychology*, *63*, 726–737. doi:10.1080/17470210903137180

Yang, T., Gathercole, S. E., & Allen, R. J. (2014). Benefit of enactment over oral repetition of verbal instruction does not require additional working memory during encoding. *Psychonomic Bulletin & Review*, *21*, 186–192. doi:10.3758/s13423-013-0471-7

Yeung, N. (2010). Bottom-up influences on voluntary task switching: The elusive homunculus escapes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*, 348–362. doi:10.1037/a0017894

Young, R. M., & Lewis, R. L. (1999). The Soar cognitive architecture and human working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 224–256). Cambridge, England: Cambridge University Press.

Zbrodoff, N. J. (1999). Effects of counting in alphabet arithmetic: Opportunistic stopping and priming of intermediate steps. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 299–317. doi:10.1037/0278-7393.25.2.299