Multi-component Working Memory System with distributed executive Control
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Running Head: WM with distributed control

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Abstract
The working memory model with distributed executive control accounts for the interactions between working memory and multi-tasking performance. The working memory system supports planned actions by relying on two capacity-limited domain-general and two time-limited domain-specific modules. Domain-general modules are the episodic buffer and the executive module. The episodic buffer stores multimodal representations and uses attentional refreshment to counteract information loss and to consolidate information in episodic long-term memory. The executive module maintains domain-general information relevant for the current task. The phonological buffer and the visuospatial module are domain-specific; the former uses inner speech to maintain and to rehearse phonological information, whereas the latter holds visual and spatial representations active by means of image revival. For its operation working memory interacts with declarative and procedural long-term memory, gets input from sensory registers and uses the motor system for output.

Keywords: goal-directed action, goal representation, task set, inner speech, visuospatial representation, sensory registers, categorical long-term memory, procedural long-term memory, episodic long-term memory

Table 1. Answers to topical questions for the Working Memory with Distributed Executive Control model.

1 Definition. Working memory is the part of the memory system used to support goal-directed activities. This support includes maintaining the task goal, the selected way to achieve this goal, the constraints or limitations of this achievement. The WM system also maintains all interim results so as to enable continuation after task interruption.

2 Methods:
   a. Simulation and computational modelling to test feasibility of assumptions and to test model predictions against existing data
   b. Dual-tasking and load experiments (typically, but not exclusively Brown-Peterson or complex span designs).

3 Non-unitary system consisting of two domain-general modules, namely the executive memory module and an episodic buffer. The former maintains task-specific information and settings; the latter is a multi-modal store maintaining the currently important events. These two modules are assisted by modality-specific low-effort systems, namely the phonological buffer, and a visual/spatial memory. These systems interconnect with long-term memory (categorical and procedural) and the episodic buffer feeds episodic LTM. The phonological buffer is based on a medium for internal speech and is mainly used for rumination and self-instruction, but can also be used for verbal rehearsal as a phonological loop.

4 Role of attention and control. Attention plays a central role in goal-directed activities and by extension in working memory. Control processes are the result of prior learning and are retrieved from (mainly procedural LTM) when needed.
5 Storage, maintenance and loss of information. Executive memory is dedicated to maintenance of the current task-set and its constraints. The episodic buffer stores instances of the events as they occur by combining perceptual information, declarative knowledge and episodic LTM. These two modules are capacity limited in terms of total amount of activation. As total activation exceeds the capacity limit, activation of the individual events in the stores is decreased proportionally. This allows for a choice between a few strongly activated traces or a larger number of traces that are less strongly activated and hence not so readily accessible. A refreshment mechanism in the episodic buffer allows selective activation increase for targeted instances (because when the capacity limit is reached, increased activation of one event has to be compensated by decreased activation in the other events). There is no such limitation to the amount of information in the modality-specific systems, but limitations are incurred due to automatic and fast decay, which can be counteracted by verbal rehearsal (in the phonological buffer), or by trace revival (in the visuospatial module). Hand in hand with the mechanisms of refreshment, the traces can be transferred to and consolidated in episodic LTM.

6 Role of LTM knowledge. On the present view, WM is not the activated subset of LTM, but it heavily relies on knowledge present in LTM; namely, it relies on declarative knowledge to interpret perceptual events and create specific instances for further processing in the working memory modules, and it relies on procedural knowledge to activate and select procedures to act on the working memory contents.

7 Findings inconsistent with the model. At present, WMDEC cannot yet account for priming effects that are typically accounted for by spreading activation in LTM because a more complex mechanism is required within the context of the model. Although WMDEC should in principle be able to account for the Hebb learning effect, precise predictions cannot be formulated until the functioning of episodic LTM is further developed within the model.

8 WM development. WMDEC does not pretend to explain developmental changes, but if anything, it may be assumed that some of the modules within the model come into existence at different times during development.
The Working Memory with Distributed Executive Control (WMDEC, Vandierendonck, 2016b) model was developed in order to deal with issues of executive control in the context of working memory while avoiding explanations that invoke a homunculus. The model shares some assumptions with the Multicomponent Working Memory (MWM) model (A. Baddeley, 1986, 1996b, 2000; A. D. Baddeley & Hitch, 1974; A. D. Baddeley & Logie, 1999; A. Baddeley, Hitch, & Allen, this volume), and although that model yields a pretty good account of a number of observations regarding working memory, it unfortunately continues to call on the central executive, which—even after several attempts at fractionation (e.g., A. Baddeley, 1996a)—remains a powerful agent. However, research has shown that it is feasible to decompose the central executive into more elementary processes, such as input monitoring, response selection, memory updating, etc. (Stuyven, Van der Goten, Vandierendonck, Claeyys, & Crevits, 2000; Szmalec, Demanet, Vandierendonck, & Verbruggen, 2009; Szmalec & Vandierendonck, 2007; Szmalec, Vandierendonck, & Kemps, 2005; Szmalec et al., 2008; Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011; Vandierendonck, Szmalec, Deschuyteneer, & Depoorter, 2007). Hence, a model with distributed control instead of a central executive agent is preferable and possible, as is also suggested by Logie (2016; R.H. Logie, Belletier, & Doherty, this volume).

The WMDEC model conceptualises working memory (WM) by means of a number of maxims about the characteristics of WM as a system embedded in cognition strongly linked to goal-directed action (see also Table 2). The first maxim states that WM provides temporary memory storage in support of any goal-directed action, whether consciously or unconsciously planned. This idea was first proposed by Miller, Galanter and Pribram (1960) in their thought-provoking book, Plans and the Structure of Behavior. On this view, WM is not only needed to store the goal (cf. findings on goal neglect, Duncan et al., 2008), but also to keep track of interim results of task execution and furthermore also to keep focus on the ways to achieve the goal and the physical and mental constraints and limitations imposed on goal attainment. Note that this maxim not only applies to deliberate conscious actions but also to actions to fulfil particular needs (hunger, thirst, curiosity, etc.) and that
this concerns more than calling on prospective memory as implied by Cowan (2017).

A second maxim is rooted in the observation that language and verbal representations strongly dominate human cognition, such that all knowledge and all processes using this knowledge are pervaded by language and language-based representations. This is also true in the context of memory, as shown by Morey, Morey, van der Reyden and Holweg (2013): visuospatial task performance is dramatically disrupted by the presence of a verbal memory load, while a visual memory load has almost no effects on verbal task performance. This central role of language encoding is also evident in task execution and switching between actions. More specifically, the presence of an articulation task in a task switching sequence strongly affects performance, such that the task switch cost (slower and more error-prone task execution) is decreased when the articulatory activity supports maintenance of the task goal (e.g., repeating the task name, Goschke, 2000), whereas the switch cost becomes much larger when the articulatory task is irrelevant to the task (A. Baddeley, Chincotta, & Adlam, 2001; Goschke, 2000; Saeki & Saito, 2004), but other motor tasks such as foot-tapping do not affect the switch cost, showing that the concurrent articulation effect is not merely a dual-task effect (Emerson & Miyake, 2003; Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, 2005). Furthermore, the cost of switching between arithmetic tasks is less impaired when transparent cues (+ and -) than when nontransparent cues (red and black) are provided, while the effect of articulatory suppression is not modulated by task difficulty or the number of different tasks in the switching procedure, and remains overall much stronger than the interference due to foot-tapping (Emerson & Miyake, 2003). This leads to the conclusion that self-instruction by means of inner speech is the driving factor behind these effects (see also Miyake, Emerson, Padilla, & Ahn, 2004). So, the point of importance is that language is so dominant that we, humans, speak to ourselves to give instructions, to remind ourselves what we have to do, to remind ourselves of pitfalls, etc. In short, the second maxim states that the WM system includes an inner speech mechanism that supports self-instruction (cf. Posner & Rothbart, 2007; Vygotsky, 1962), but that can be used to support rehearsal, rumination and mind wandering, to the extent that it is not occupied for other purposes, such as self-instruction.

The third maxim concerns the role of control processes. WM has always been conceived of as a short-term memory system endowed with control processes (e.g., Atkinson & Shiffrin, 1968, 1971; Shiffrin & Atkinson, 1969). Control processes were considered to be optional, meaning that their usage either depended on an instruction to utilise these processes, or on a decision on the part of the memoriser to do so. While some of these control processes are rather simple and straightforward, such as coding and rehearsal, others, such as decision making or deploying rehearsal strategies may require rather elaborate processing and continuous control. With the introduction of dual task and selective interference methods, even more complicated controls could be considered. No wonder, some theories outsourced these controls to an executive agent. Clearly, control processes are part and parcel of a WM system and without control processes WM is simply a
short-term store. Hence, any model has to find a way to deal with these processes. Collecting them all in a central agent entails the danger of creating a closed box that performs the control while nobody has an idea what is going on. The only way out is to accept that control processes are bound to particular conditions that trigger a previously acquired autonomous action that resolves the issue at hand.

The fourth and final maxim holds that WM is an extremely versatile and flexible system that allows information to be stored in a modality-specific code most adapted to the current situation. These modality-specific representations allow to preserve characteristics of the perceptual input, such as a phonological/articulatory code suitable for the inner speech mechanism or a visuospatial code for visual patterns, schematic layouts, etc. Apart from such modality-specific or domain-specific coding also cross-modal or domain-general codes are needed to represent information without preserving perceptual features or to bind representations from different perceptual input channels. That these encoding formats imply flexibility means that the person has a choice as to which encoding best fulfils the present needs.

Table 2. Maxims underlying the Working Memory with Distributed Executive Control model.

<table>
<thead>
<tr>
<th>1. Working memory provides temporary storage space for consciously and unconsciously planned actions so as to remember the current goal, the progress towards goal attainment, the ways to attain the goal, and the physical and mental constraints and limitations imposed.</th>
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<tbody>
<tr>
<td>2. Working memory includes an inner speech mechanism that allows self-instruction, but can also be used for rehearsal, mind wandering and rumination.</td>
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<tr>
<td>3. Control processes are an inherent part of working memory. The application of a control process can only occur if a particular condition exists. Detection of the condition triggers the autonomous execution of the process resulting in the disappearance of the triggering condition.</td>
</tr>
<tr>
<td>4. Working memory is a versatile and flexible system that allows different encoding formats and different levels of generality of the representations.</td>
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</table>

These four maxims specify the conceptualisation of the WM system proposed in this chapter. In terms of the various definitions reviewed by Cowan (2017), it can easily be seen that the present conception is based on a combination of the life-planning definition (Miller et al., 1960), the multicomponent definition (A. Baddeley,
1986, 2000; A. D. Baddeley & Hitch, 1974), and the attention-control definition (Engle, 2002; Mashburn, Tsukahara, & Engle, this volume).

Figure 1. Working memory modules and their interconnections. The procedural loop (dashed closed arrow) continuously compares iconic and echoic sensory memory and the working memory modules to condition-action rules stored in Procedural LTM. Among the matching rules one is selected for execution (routes 3 and 4). Sensory events are interpreted with the help of Categorical LTM and are instantiated in the Episodic Buffer via routes 1 and 2. Additionally, verbal events can be encoded in the Phonological Buffer (route 5) and visual events can be encoded in the visuospatial module (route 6). Over time the contents of the episodic buffer flow over into Episodic LTM via route 8. Route 7 shows the existence of interconnections between the episodic buffer and executive memory; these are realised via procedural LTM rules.
Structure of the Working Memory System

The WM system not only offers support for the control of goal-directed actions, it also provides an interface between perception and knowledge. Information coming in via the perceptual channels contacts the knowledge base stored in long-term memory which allows to interpret the perceived events (apperception, Wundt, 1874). Since the work of Sperling (Averbach & Sperling, 1961; Sperling, 1960), it is known that perceptual processes leave very short-lived memory traces in so-called sensory registers, such as the iconic and echoic sensory memory for respectively visual and auditory processing. As these memories only yield a brief extension of the perceptual events, the WM system is used to maintain a more endurable trace of the events of interest (see also Atkinson & Shiffrin, 1968). Figure 1 shows a schematic overview of all the storage modules included in the present WM model as well as the interrelations between the different modules. Table 1 explains the characteristics of the model according to a scheme that allows comparison of the models in the present book.

According to the present model, the WM system uses both modality-specific and domain-general storage facilities for maintaining such more endurable traces. When these memory traces include an important number of perceptual features, modality-specific storage systems are convenient. In principle, it is possible that every perceptual modality has a corresponding modality-specific storage module. Which modality-specific modules should be included is an empirical question as well as an issue of theoretical parsimony. In view of the dominant role of language in cognitive processing, a verbal-phonological module based on an inner speech mechanism that mediates self-instruction (cf. Vygotsky, 1962) is included. Furthermore, there is sufficient evidence in favour of a dissociation between modality-specific phonological storage on the one hand and visuospatial storage on the other hand (e.g., Hamilton, 2011; R. H. Logie, 2011; R. H. Logie, Zucco, & Baddeley, 1990; Parmentier, 2011). Some evidence even suggests a dissociation between visual and spatial storage (Klauer & Zhao, 2004), but some commonalities between both can still be defended because this dissociation is likely to be more functional than structural. In other words, according to the present state of the art, at least phonological and visuospatial working memory modules should be included.

Accordingly, the phonological buffer maintains phonologically\(^1\) encoded information. This maintenance is volatile as it is easily “overwritten” by newly incoming phonemic information and by inner speech acts that are unrelated to the stored information; it is also vulnerable to decay, such that without any further action after a few seconds the phonological codes can no longer be accessed. Such

\(^1\)Because the qualification “phonological” (as in the terms “phonological store” and “phonological loop”) is widely used, this label remains also in place for referring to the phonological buffer in the present model. However, considering that the proposed module uses inner speech, it would obviously be more convenient to call it “articulatory buffer”, in particular because it encodes in terms of articulation (output lexicon) rather than perception (input lexicon). Note however, that the term “articulatory loop” was at some occasions also used by Baddeley and colleagues.
automatic information loss or decay can be counteracted by verbal or articulatory 
rehearsal: by processing the information in the phonological buffer via the inner 
speech mechanism (phonological loop), the information re-enters the phonological 
buffer resulting in a renewed trace.

Visuospatial information is maintained in the visuospatial module. As the term 
suggests, this module contains visual information linked to a particular spatial 
location or delimited area in surrounding space. A number of objects (minimally, 
shapes with a particular texture or colour) can, for example, be present in different 
spatial locations; these objects and locations are represented in the visuospatial 
module, which allows for recall of the objects (shapes or colours or both) and the 
location at which objects are present. Although humans are able to represent 
complex images of such situations at a rather global level, it is difficult to maintain all 
the details for all the elements of the complex image. With respect to the example 
of a number of objects as given here, it is difficult to maintain for every object the 
correct binding of shape, colour and location. As with the phonological buffer, the 
information maintained in the visuospatial module can easily be disrupted by new 
visual images or objects changing location and the information present also suffers 
from decay. Although the debate as to whether a kind of rehearsal mechanism 
exists also for visuospatial materials, on the grounds that imagination may help to 
reconstitute or revive an image, in the present model, it is assumed that visuospatial 
information can be reprocessed and restrengthened by means of revival. Such 
revival may be based on visual imagination but also on imagination of performing an 
action on an object. Hence, research on memory for action (Engelkamp, Zimmer, 
Mohr, & Sellen, 1994; Koriat, Benzur, & Nussbaum, 1990; Mulligan & Hornstein, 
2003; Yang, Gathercole, & Allen, 2014) as well as earlier work on the so-called 
“inner scribe” by Logie (R. H. Logie, 1995; e.g., R. H. Logie & Pearson, 1997) is 
highly relevant in this context.

Episodic Buffer

Apart from these two modality-specific modules, the present model also 
includes two domain-general modules each with a specific purpose. The first of 
these is the episodic buffer (similar to the conception first formulated by A. Baddeley, 
2000) which maintains domain-general or cross-modal memory traces. According to 
the present view, these traces start as temporary records but after consolidation² 
become part of episodic long-term memory, as is also shown in Figure 1. The 
episodic buffer is the main storage module of the WM system which may be 
supported by the modality-specific modules in cases where maintenance of the 
perceptual (auditory and/or visual) features is crucial. It is the central medium for 
temporary maintenance of information, because this module is needed to maintain 
cross-modal links, and to create links to existing knowledge. Because of this 
mixture, this module contains representations that can easily access either of the 
domain-specific storage systems as well as semantic or categorical long-term 
memory. As a consequence and in contrast with a number of views within the field

² The term “consolidation” as used in the present chapter refers to long-term consolidation. This should not be 
confused with the same term used to refer to short-term consolidation (or transfer from sensory to working memory).
(e.g., Atkinson & Shiffrin, 1971; Cowan, 1999; Cowan, Morey, & Naveh-Benjamin, this volume; Oberauer, 2009, this volume), this module cannot be considered as activated categorical LTM. Instead, modality-specific information and knowledge are combined into a specific instance embodying the combination of all these features. Because the episodic buffer consists of instances or tokens that may be linked to more general information in categorical LTM (types), the process is called instantiation (see also Vandierendonck, 2016b). Within the present model, it is assumed that the episodic buffer does not suffer from decay. However, it has a limited capacity with respect to the strength (degree of activation) of the traces being maintained, so that it is possible to keep a few items at high strength or to keep more items at the cost of having a small activation strength for all or almost all the items in the store. Loss of information from the episodic buffer is due to interference and suppression of traces that are no longer useful. When this capacity limit is reached, each time a new trace is added, the older traces lose some of their strength. After a few new traces have been added, some of the older traces may become so weak as to be useless; either these older traces get lost or they regain strength by applying a strengthening mechanism similar to rehearsal and revival in the modality-specific modules, namely attentional refreshing (e.g., Camos et al., 2018; Johnson, 1992; Johnson et al., 2005; Vergauwe & Cowan, 2015).

Refreshment consists of paying attention to or thinking of the represented information for a short time and the result is that the trace becomes stronger; inevitably this gain of strength occurs at the expense of the strengths of the other traces when the buffer is occupied to full capacity.

Within the present view, refreshment does not only result in a prolonged maintenance of a trace in the episodic buffer, it also involves consolidation, which means building and strengthening a trace in episodic LTM. Transfer of information of short-term to long-term storage was an attribute of rehearsal (elaborative rehearsal, Craik & Watkins, 1973) in some of the older short-term memory and working memory theories (e.g., Atkinson & Shiffrin, 1968; Broadbent, 1958; Norman, 1968), but it is at odds with views that consider working memory to be essentially activated long-term memory. However, to the extent that working memory is also considered to collaborate on the creation of episodic traces, it remains a useful idea. In the present view, consolidation—transfer to episodic LTM—is associated with refreshment and not with revival or rehearsal because the latter actions are assumed to run off automatically and hence do not involve attention. However, rehearsal can occur jointly with refreshment (which would yield elaborative rehearsal) and also revival can be performed jointly with refreshment. These joint maintenance modes ensure that not only domain-general, but also modality-specific information can enter long-term episodic memory.

Executive Memory

The second domain-general module is specific for the maintenance of task and goal-related information and because of its crucial role in task execution, it is referred to as the executive module or executive memory. Unlike the central executive in some WM models (e.g., A. D. Baddeley & Hitch, 1974; A. D. Baddeley & Logie, 1999; Cowan, 1999; Cowan et al., this volume), this module only maintains
task-relevant information, such as the task set. Whereas the task goal is part of our general knowledge as maintained in categorical LTM, it can easily be instantiated in the episodic buffer with or without articulatory support from the phonological buffer, or visuospatial support from the visuospatial module. Similarly, the information which has to be processed in the task, and interim results that are obtained by task processing are represented in the episodic buffer, again with or without support from the modality-specific WM modules. A small example may clarify which representations can be maintained in the episodic buffer and which ones would have to be held in executive memory. Consider an experiment in which participants are requested to report the sum of two numbers (e.g., “27 + 35 = ?”) presented in the centre of the screen, with the instruction to respond fast but correctly. As already argued, the task goal (adding numbers) will be maintained in the episodic buffer. As each sum is processed, the interim results will also be kept active in the episodic buffer until the final outcome is reached. More specifically, for the given example, the participant may decide to first sum the units (7 + 5 = 12) and maintain 12 in the episodic buffer, next sum the tens (20 + 30 = 50) and also keep this result in the buffer. Finally, these outcomes must be combined: 50 + 12 = 62 before reporting this outcome and clear the interim results from the episodic buffer. In order to perform all these actions, some necessary information has to be maintained, namely to orient attention at the digits on the screen and to keep speed and accuracy of responding in balance. This information is part of the task set as it relates specifically to task execution. Therefore it is maintained in executive memory.

It could be argued that the episodic buffer as a domain-general module is perfectly equipped to maintain the latter kind of information. If the buffer would maintain the task set, a competition would be expected between task-related and content-related calls on WM capacity, but this expectation is contradicted by some findings regarding the relationship between WM and task switching. As already mentioned, some studies show that task switching relies on working memory, more in particular on the phonological loop. Yet, several studies have failed to report effects of a memory load on task switching (Kiesel, Wendt, & Peters, 2007; Lefooghe, Barrouillet, Vandierendonck, & Camos, 2008; Logan, 2004). Similarly, in the opposite direction, no effect of the number of task switches on working memory performance is observed when no timing constraints are imposed (Logan, 2004, 2006); only when the retention interval is strictly timed, the number of task switches affects working memory performance (Lefooghe et al., 2008). These findings converge on the conclusion (see Vandierendonck, 2016b for a more extensive argumentation) that although task processing seems to call on working memory resources, this processing does not compete for resources involved in the maintenance of content, such as the maintenance of task names in Logan (2004) or irrelevant content, as in Kiesel et al. (2007). By including a separate module for task-related information, it is ensured that task-related and content-related processes do not have to compete for storage space, and in addition, everything related to task control is available in one single module, so that information needed for proactive control of task execution is grouped within executive memory.
Because executive memory maintains task-related information, namely a representation of the action or actions that lead to goal achievement and the constraints imposed on the allowable actions, it may be concluded that this module is the same as the procedural working memory module in Oberauer’s working memory model (Oberauer, 2009, this volume). For a number of reasons executive memory must not be equated with procedural working memory. First, in the present conception, when a production rule in procedural LTM matches the WM contents and is selected for execution, it is activated which results in execution of the action part of the rule. This execution may entail a change to any of the WM modules or the initiation of a motor action, but the rule itself does not remain activated after this and does not become part of WM. In other words, there is a fundamental asymmetry between declarative (categorical, semantic, …) LTM and procedural LTM in that activated declarative LTM contents are maintained as part of the instances in the episodic buffer and/or in the domain-specific WM modules while activated procedural LTM elements are immediately executed and do not become part of WM contents. The contents maintained in executive memory have declarative origins, but relate to task-execution. In contrast, in Oberauer’s conception, procedural WM is activated procedural LTM in symmetry to the activated declarative LTM contents that constitute declarative WM.

As the arithmetic example suggests, the task set concerns orientation of attention and speed-accuracy balance. In fact, a task set generally contains information about the means by which the goal can be attained, the modality which is used for responding, and which particular conditions constrain the execution of the actions (e.g., Logan & Gordon, 2001). The task set can best be conceived as a cognitive schema, such as a frame or a script (e.g., Abelson, 1981; Graesser & Nakamura, 1982) that is part of our acquired knowledge (categorical LTM). As is typical for such acquired cognitive structures, some of the elements of the structure are fixed, while others can vary and may or may not have a default value.

Like the episodic buffer, the executive module has a limited capacity, but does not suffer from decay. Executive memory maintains maximally a few task sets. As each task set consists of a number of components (parameters, actions, mappings, …), each of these components occupies some of the available capacity. If executive memory contains more than one task set, the one with the strongest activation is dominant and will be accessible to monitor task progress. When more executive memory elements are made active, the already present task sets and their components will lose some strength to allow the newly uploaded task set to consume some capacity.
Functioning of the WM System

At any moment in time, the components of the WM system contain representations originating either from environmental events (represented in sensory memory) or from internal events triggered via associations between WM contents (in episodic buffer, phonological buffer, the visuospatial module and executive memory) and LTM representations. A production system similar to that underlying ACT (Anderson, 1983; Anderson & Lebiere, 1998; Lovett, Reder, & Lebiere, 1999) governs changes to WM contents. The production system consists of a set of production rules (also known as if-then rules) stored in procedural LTM and a procedural loop (see Figure 1) that governs activation, selection and execution of one rule at a time. An example of such a rule is “IF x is a new object in iconic sensory memory AND x is not present in the episodic buffer THEN create an instance of x in the episodic buffer”. The example shows that the IF-part (condition) may consist of several elementary conditions joined by the the AND-operator. The more of such elements are included in the rule’s condition, the more specific the rule is. Apart from the degree of specificity, each rule also has a strength which can change by experience. When two or more rules leading to the same action match WM contents, only the most specific of these rules will enter the competition for selection. Among the matching rules, one is selected and the rule action (“create” in the example at hand) is executed. This execution may take some time; during this interval, the rule is occupied and cannot be selected again until the creation is completed. At a fixed rate, a cycle of the procedural loop is executed. During a cycle all production rules stored in procedural LTM are compared to the WM contents, and among the available rules that match the WM contents, at most one rule is selected for execution of its action. Each rule has a strength that determines the likelihood that it will be selected if it matches.

In order to better clarify the dynamics of this system, its operation in a few characteristic task settings will be described, namely in serial recall and in a complex span task. Each case is illustrated with the help of a concrete example so as to clarify how each part of the system contributes to WM operation.

Serial Recall

Consider a test situation where participants have to memorise consonants (W, T, Z, P, R, F, N) presented visually at a fixed rate of 1 per second for immediate recall in the order of presentation. A short instruction explains that the start of presentation will be announced by a visual signal, that each letter will be presented in the centre of the screen, that at the end of the list, the word “recall” will appear, after which recall of the letters can be given orally in the same order as presented, and that the time allowed for recall is limited. This is followed by a short practice session. Focus here is on a single experimental trial, as illustrated in Figure 2.

The start signal catches attention; it becomes represented in the episodic buffer (by a rule such as the one shown above). This signal is used as a cue to retrieve the memorisation-and-recall goal from categorical LTM and to keep it active in the episodic buffer. In its turn the goal representation will match a rule that
retrieves and configures a corresponding task set in executive memory. This task-set representation includes the specifics of the task at hand, namely that recall will

Figure 2. Contents of episodic buffer and executive memory during learning and serial recall of a sequence of consonants (example explained in text). Instantiation of the cue matches a rule to load the task goal (1) which in its turn matches a rule to retrieve the task set and its components from LTM (2). As each letter is presented, it is instantiated in the episodic buffer (3-9) and refreshed as specified in executive memory. Finally, the recall signal triggers an adaptation (10) of the task set parameters (recall OFF to ON) so that the recall action can become active.
be oral ("Modality ORAL"), and that recall will be required later ("Recall OFF"). Typically, also other settings will be included, for example, that stimuli are presented visually, that recall will be required when the recall signal is presented. Furthermore, some self-instructed issues of importance may be included: one such element may be how received information is maintained ("Maintain REFRESH"), but this could also have been specified by instruction. When the first consonant (W) is shown, it enters iconic sensory memory and is for a short period of time available as a "new" event (environmental change), so that it may match a rule that results in the creation of a representation. As part of the creation, categorical LTM is accessed to retrieve the meaning and relevant properties of this stimulus event; these properties are then used to create an instance in the episodic buffer. During creation, the letter will be tagged as "to-be-remembered" and associated to the current time signal; this allows recovery of instance order in the to-be-remembered sequence. In the time remaining until the presentation of the next letter, a rule to refresh and consolidate the letter may be executed. When the next consonant is presented, it is instantiated in the same way, and in the remaining interval, both letters presented thus far will be refreshed one at a time. This continues for each letter in the sequence, but at some point, the interval will not be long enough to refresh all the letters; nevertheless refreshing continues where it left off after the previous letter. At the end of the sequence of consonants, the recall signal is presented, which becomes also encoded in the buffer as a cue to start recall. This triggers the application of rules to change the setting for the recall parameter in the task set (to "Recall ON") and the action setting for recall is implemented changing the task action from maintenance to recall. Based on the remembered instructions, the recall setting will include the specification for the order requirement. A rule to retrieve the stored information will now match the task settings in executive memory and the oldest letter is searched for. Once the oldest letter is found, first access is attempted in the episodic buffer, and if that is not possible, episodic LTM access is tried. If either access succeeds, the instance is tagged as recalled and preparations for output are started; until this process completes, recall of the next item is not possible, but meanwhile the other letters may be refreshed. If access fails, it will be tried again. The probability that access succeeds depends on the activation strength of the stored element. On average, the lower the activation strength the more attempts for access will be needed. However, because several of the elements will have accrued strength in episodic LTM as well, recall may still be successful. After a number of attempts without success, recall will shift to the next oldest element.

The elaboration of this example was completely based on the usage of the episodic buffer as only storage medium. If the phonological buffer were used as the main storage medium, which is perfectly possible in this task, the events would be roughly the same, but instead of preparing for refreshment, a preparation for rehearsal would be in order (different setting in the task set, namely “Maintain REHEARSE”). For maintenance, a phonological loop would be started, initially with the first consonant as single element. The maintenance would thus continuously perform the subvocal articulation of this consonant. As more letters enter storage, the loop would be extended with these consonants in the order of occurrence and rehearsal would perform subvocal articulation of each consonant in turn. When
Figure 3. Episodic buffer and executive memory contents in a complex span task with execution of parity task trials in the between-letter intervals of a serial memory task. Parity and memory goals are coordinated under an over-arching dual-task goal. First the memory task and the corresponding task set become active and dominant, until the parity task becomes dominant (as soon a digit is presented). If inter-digit time allows, the memory task regains dominance to allow for refreshment of the memoranda. This continues until all the digits have been presented and the next letter or the signal to recall appears. At that point, the recall parameter and action in the memory task set are adapted for this requirement.
during the presentation interval between two consonants, not enough time is left to rehearse them all, rehearsal will continue, but will be selective. Note that in this case episodic buffer representations are not refreshed, unless the episodic and the phonologoical buffer would be used jointly. When the recall signal is presented, recall will start from the contents of the phonological buffer, consulting also the episodic buffer and episodic LTM if access does not immediately succeed.

**Complex Span**

In a complex span setting, the memorisation and recall context is combined with execution of another task: in the intervals between the presentation of the memoranda one or more simple cognitive tasks have to be performed. In other types of dual-tasking situations (also known as Brown-Peterson procedure), the tasks are presented during the overall retention interval of the memory task. In terms of WM operation, these two contexts are quite similar. Here, an example of a complex span context is considered in more detail. The participant is presented with a series of letters for later recall in the correct order. In between two letters, another task is presented. Among the many different possible tasks, such as verification of arithmetic sums (e.g., Turner & Engle, 1989), sentence comprehension (e.g., Daneman & Carpenter, 1980), simple reasoning tasks (e.g., A. D. Baddeley & Hitch, 1974), counting (e.g., Case, Kurland, & Goldberg, 1982), in the present example, a parity judgment task is used (e.g., Barrouillet, Bemardin, Portrat, Vergauwe, & Camos, 2007). The details are illustrated in Figure 3.

In this type of situation the memory task and the parity task become alternately dominant within a single memory trial: the memorisation task is interrupted to perform some parity trials but continues afterwards; similarly after execution of the parity task, the parity goal should not be dismissed because more parity trials are to follow. In such a context, a coordination of the two goals is needed. This allows the goals to become dominant in turn, but remain active in WM. Thus, relevant memory information is maintained and the parity task must not be prepared and configured every time a new digit appears. In Figure 3, this is shown by the representation of a dual-task goal in the episodic buffer. Although, this is not simple, humans are very well acquainted with that kind of requirement as well in dual-tasking contexts as in the context of problem solving where the main goal often requires subgoals to be attained in order to solve the problem. Once the dual-task goal is set, the memorisation goal and the parity goal are added as subsidiary goals. Presuming that a practice session has been given, at the start of the first complex span trial, the three goals (dual-task, memorisation and parity) are already stored in the episodic buffer and the two task sets in executive memory are also completely prepared. The parity task set differs slightly from the memorisation task set in that some of its parameters differ; additionally, the parity task set requires category-response mappings instead of stage-specific actions. As soon as a letter appears, the memorisation goal is activated to become dominant over (i.e., more strongly activated than) the parity goal and the memorisation task is made dominant over the parity task set. Note that if this would not be the case, letters would be treated by the parity task or in the reverse situation digits would be memorised instead of judged for parity. As long as no new information comes in, the already
present letters are refreshed and consolidated. When a digit appears, the parity goal is made dominant over the memorisation goal and the parity task set is activated to be stronger than the memorisation task set. The settings ensure that the digit is categorised as odd or even and that the required response is initiated and emitted. As soon as the response is initiated, the memorisation goal and task set will be activated to be dominant so as to enable further refreshment. When the next digit appears, dominance shifts again to the parity goal and task set. These alternations continue until the recall signal appears at which time recall is initiated and the trial finishes, with some empty time before the next trial starts.

Executive Control

The operation of the WM system in all these examples was explained without explicit reference to executive control processes. In fact, the representations in executive memory serve to support proactive control processes, namely to maximise the chance that the task goal is attained by the selected action sequences. The task settings in executive memory ensure that only condition-action rules matching these settings can be selected. Overall, such proactive control works quite well but not perfectly, because WM may contain representations that are no longer relevant for the current goal. Moreover, many stimuli can be handled by several tasks (e.g., digits can be categorised on the basis of magnitude or parity) and this increases the likelihood that a lingering trace from a previous trial interferes with the processing required in the present trial. In order to avoid such processes to result in errors, reactive executive control can be applied.

To clarify this notion of reactive control, consider the difficulties one may encounter when performing the Stroop task, i.e., identifying or naming the ink colour of printed colour words (e.g., when shown the word “red” printed in blue, say blue). On incongruent trials, the task is difficult because reading is highly automated and produces the colour name (red) faster than the process of identifying/naming the ink colour (blue). In such a situation, a response conflict is present: a response tendency to say red as well as a response tendency to say blue become active. If there is a preference for fast responding, saying the colour name is more likely than saying the ink colour, with an incorrect response as result. With a preference for slower responding, the proactive control mechanisms allow the correct response tendency to become stronger, so that it may win the competition, resulting in a correct answer. In contrast, congruent trials do not suffer from this difficulty because there is no response conflict: both processes (colour identification and colour reading) activate the same response. In this task context, reactive executive control can come into play if the response conflict is detected (Botvinick, Braver, Barch, Carter, & Cohen, 2001). After conflict detection, reactive control can be deployed by changing the speed-accuracy balance in favour of slower and more correct responding. This results in the so-called Gratton effect (Gratton, Coles, & Donchin, 1992): the congruency effect (slower and more error-prone responses on incongruent trials) is decreased after an incongruent trial compared to a previous congruent trial. Research has shown that such reactive corrections only occur if
one is aware of the presence of a response conflict, irrespective of whether a conflict was present (Desender, Van Opstal, & Van den Bussche, 2014).

Reactive executive control does not only occur to monitor and adapt response conflicts. A large amount of evidence has been collected regarding the presence of such control processes also in task switching, response inhibition, and attentional control. Because these control processes seem possible without awareness, are task or context-specific and are sensitive to reward, it has been suggested that these processes are routed in associative learning (Abrahamse, Braem, Notebaert, & Verguts, 2016). Given this associative basis, both conflict detection and reactive corrections such as changes in attention or in speed-accuracy balance can be handled by condition-action rules that result in changes to the task set parameters.

Whether this is also the case for all kinds of executive control, is at present still an open question. According to Norman and Shallice (1986) executive control is required in situations that involve planning or decision making, involve troubleshooting, situations where responses are not well learned or contain novel action sequences, in dangerous or technically difficult situations, and situations that require overcoming of a strong habitual response or resisting temptation. The last set of situations overlaps with the control processes examined by Abrahamse et al. (2016), but the other four sets of situations seem to refer to higher cognitive processes that require some particular skills and some even require a sufficient degree of experience. An account of such processes is welcome, but requires further research.

**Empirical Support**

The WMDEC model was presented for the first time at the International Working Memory Conference at Cambridge in 2014, and published subsequently (Vandierendonck, 2016b). A computational version providing a proof of concept (Vandierendonck, 2012) had been published earlier. Two sources of support for the model will be considered in turn: findings from simulations with the earlier computational version of the model and predictions following from the properties of the model. Finally, also limitations and shortcomings related to the design choices will be discussed.

The model was designed in the first place to account for working memory usage in task switching and other kinds of multiple task situations. The early simulation work (Vandierendonck, 2012) shows that the model accounts for the findings regarding the task span procedure (Logan, 2004) and the findings regarding the number of task switches in the strictly timed complex span and dual-task designs (Liefooghe et al., 2008). In the task-span procedure, participants are presented a series of task names they have to remember in the correct order (memory span) and which they also have to execute in the correct order (task span). Over a series of experiments that varied length of the sequence, number of task switches, and opportunities for chunking, Logan (2004) reported that the memory span (number of correctly remembered task names in the correct order) and the
task span (number of correctly executed tasks in the correct order) did not differ. This was taken as evidence that task performance and memory maintenance are not mediated by the same WM resource. The strictly timed procedure used by Lieflooghe et al. (2008) involved presentation of series of letters for later serial recall with digit judgments tasks intervening between letters (complex span) or in the recall interval (Brown-Peterson procedure). The number of task switches in these task sequences was varied, and it was found that when more task switches were required, memory for letters was poorer. While the TBRS model obviously accounts for the latter finding, to my knowledge, WMDEC is the only model to account for the task-span findings. By design, the model can also account for findings that a task executed for the first time may show congruency effects (Lieflooghe, Wenke, & De Houwer, 2012; Meiran & Cohen-Kdoshay, 2012), because also for a new task, a task set is configured in executive memory on the basis of a generic task-set schema acquired from previous experience.

Next, the focus is on showing that the model can account for a number of important findings with respect to working memory performance. As the present full version of the model exists only as a verbally formulated model, it is easy to claim that it can account for many findings. For a fair test, however, it would be far more acceptable to show that a computational version of the model accounts for the findings. Currently, a computational version covering as much as possible of the present model is being developed with the aim of running a series of simulations of findings considered to be important and critical. However, for reasons exposed elsewhere (R. H. Logie, 2018; Vandierendonck, 2018) the model’s predictions will not be checked against a list of so-called benchmarks (Oberauer et al., 2018). Instead, the model’s predictions will be compared to findings considered relevant to the purpose of this model. The focus is on predictions that follow from the fact that WMDEC shares properties with other models and frameworks in the field.

WMDEC shares a large number of features with the multicomponent model (see e.g., A. Baddeley et al., this volume; R.H. Logie et al., this volume). Therefore, the model may be expected to account for modality effects in working memory, namely that a secondary task in the same modality as a primary memory task interferes more than a secondary task in a different modality. Because of the articulatory basis of phonological buffer in the present model, like the multicomponent model, WMDEC predicts a word length effect. In a similar vein, on the basis of revival of more complex visual and spatial patterns, a complexity effect is predicted, namely that more complex visuospatial sequences are remembered less well (Kemps, 1999, 2000, 2001; Parmentier, Elford, & Maybery, 2005; Rossi-Arnaud, Pieroni, & Baddeley, 2006). However, because the model assumes that maintenance of serial order requires the presence of a recall intention, it predicts that serial recall in a primary memory task will be more impaired by a secondary embedded memory task when it also requires ordered recall than when it requires item (unordered) recall irrespective of whether the tasks call on the same or different modalities (Depoorter & Vandierendonck, 2009; Vandierendonck, 2016a).

Although the assumptions of the present model and the TBRS model (e.g., Barrouillet, Bernardin, & Camos, 2004; Barrouillet & Camos, 2010, this volume) are
substantially different, the predictions made by both models overlap to a large extent. According to TBRs, attention has to be shared in an all-or-none fashion between activities competing for attention, so that during memory refreshment, attention is not available for other tasks, and conversely while task processing is going on, attention is not available for memory maintenance resulting in decay of the working memory traces. Thanks to rapid shifts of attention from one activity (e.g., memory maintenance) to another (e.g., secondary task), attention can be shared over a time interval. Within TBRs, cognitive load is defined as the proportion of time occupied by non-memory activity: the larger the amount of time taken up by task processing, the less time in the interval remains for attentional refreshing. Consequently, TBRs predicts that memory will suffer more, the larger the cognitive load. In fact, what happens during a maintenance or retention interval according to TBRs and according to WMDEC is very similar, so that WMDEC also predicts that when less time is available for maintenance operations (i.e., larger cognitive load), memory performance will suffer more. The only difference is in the transition between memory and task processing: whereas TBRs assumes fast switching from one to the other activity, according to the present account, these transitions have a time cost, because control has to shift from one task to another by changing the dominance relation between the two task sets in executive memory. Only a strictly quantitative test of the durations assigned to maintenance, task processing and transitions allows to distinguish between the two accounts; unfortunately, such a fine-grained empirical test is presently not feasible. It may be said, therefore, that for many of the findings reported on the basis of the TBRs model, WMDEC makes the same predictions, namely the findings reported by Barrouillet and colleagues regarding the effect of cognitive load (e.g., Barrouillet et al., 2004; Barrouillet, De Paepe, & Langerock, 2012; Barrouillet, Plancher, Guida, & Camos, 2013; Camos & Portrat, 2015; Portrat, Barrouillet, & Camos, 2008; Vergauwe, Barrouillet, & Camos, 2010).

The WMDEC model assumes that apart from domain-general attentional refreshment also domain-specific rehearsal and revival is used to protect WM representations from interference and decay. As these actions can occur independently from each other, just like TBRs, the present model predicts additive effects of refreshment and rehearsal (e.g., Barrouillet, Corbin, Dagry, & Camos, 2015; Camos, 2017), and moreover also additive effects of refreshment, rehearsal and revival.

Within the limited scope of the present chapter, it is not possible to detail all the predictions of WMDEC, but it should be self-evident that the model predicts that as the temporary maintenance requirements of mental arithmetic tasks, reasoning tasks, problem solving tasks and language processing tasks increase, such maintenance would have to compete with concurrent working memory maintenance resulting into performance decrements in either of the involved tasks (e.g., De Rammelaere, Stuyven, & Vandierendonck, 2001; Imbo, Vandierendonck, & De Rammelaere, 2007; Loncke, Desmet, Vandierendonck, & Hartsuiker, 2011; Vandierendonck & De Vooght, 1997).
As the model is relatively recent, findings that contradict the model haven’t yet been reported. However, there are some important limitations that should be mentioned. By design the model focuses on processes and effects that are directly related to goal-directed actions, which for memory-related actions implies a focus on explicit memory. As a consequence, it is not straightforward for the model to account for effects related to implicit memory events. In particular, the model does not predict priming effects that are typically accounted for by the mechanism of spreading activation (e.g., Collins & Loftus, 1975). In view of the model’s assumption that WM contents are instantiations of mostly external events in relation to an LTM representation of the events, spreading activation among LTM representations does not directly impact on WM contents. The problem of how to implement spreading activation in the model has not yet been solved.

A related concern is that the present version of the model does not predict the Hebb learning effect (e.g., Page, Cumming, Norris, Hitch, & McNeil, 2006; Stadler, 1993). Whereas the general idea for explaining this effect within the confines of the model is to assume that over trials, recurring events strengthen the recently stored event chains, a specific mechanism that achieves this has not yet been implemented. Consequently, it would be bold to claim that the model accounts for the Hebb learning effect.

In a similar vein, the current version of WMDEC makes no assumptions to account for cognitive development and inter-individual differences. No doubt, some of these differences can be captured as quantitative variations, such as speed of processing, LTM access time, capacity limitations, for which the model could provide predictions; however, considering that developmental as well as inter-person differences are likely to depend on both structural and functional differences, some further investment in appropriate assumptions would be needed to offer proper developmental and inter-individual differences accounts.

**Conclusion**

The WMDEC model defines working memory as a supportive system for goal-directed actions of all kinds which consists of domain-general and domain-specific modules for storage of contents and a domain-general module for storage of strictly task-related information used to maximise the chances of attaining the goal. This definition and the answers to the other standardised questions underlying this book project are shown in Table 1.
References


