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ROLE OF WORKING MEMORY IN TASK SWITCHING

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A review shows that task switching under memory load yields variable patterns of findings with some studies showing no interaction at all, while other studies provide evidence for an interaction. A model of working memory is presented consisting of a declarative storage component for instantiation of information and an executive storage module that contains task sets and task rules. The model is applied to two studies with very similar methodologies but yielding contrasting results, namely the task-span procedure (Logan, 2004) and the time-based resource sharing procedure (Liefooghe, Barrouillet, Vandierendonck, & Camos, 2008), when task switching is performed under a working memory load. The model accounts for the contradictory results, supporting the general hypothesis that task switching calls on working memory.

Introduction

This paper is written as part of a *Festschrift* in honour of my colleague and friend Géry d'Ydewalle. We share the same scientific ideals and values and have jointly attempted to realise a number of goals we believed to be important. Yet, we have always disagreed on the utility of the concept of working memory. Géry was not so fond of complex cognitive architectures as the one proposed by Baddeley and his co-workers to explain memory phenomena and he preferred more simple views going back to the idea that short-term memory is activated long-term memory. With this article, I hope to finally convince Géry that working memory is a complex and useful scientific construction that goes well beyond being a subsidiary of long-term memory.

Working memory (WM) is usually defined as the temporary usage of memory in the service of other tasks (Baddeley, Eysenck, & Anderson, 2009), or still broader as the maintenance of information during task processing (Baddeley, 2007; Cowan, 2005; Miyake & Shah, 1999). Examples in point are, remembering interim results such as carries in a mental calculation (Hitch, 1978; Imbo, Vandierendonck, & De Rammelaere, 2007), remembering the premisses while solving a reasoning problem (Baddeley & Hitch, 1974; Vandierendonck & De Vooght, 1997; Vandierendonck & De Vooght, 1998), remembering the words while parsing a sentence (e.g., Baddeley, 2007; Loncke, Desmet, Vandierendonck, & Hartsuiker, 2011), etc.

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The combined requirement of information maintenance and task processing makes working memory different from short-term memory (STM) which involves maintenance of information without any other requirements. For that reason, working memory is usually studied in situations that require maintenance of information while other tasks are being performed; in other words, in situations involving dual-tasking or multi-tasking. It is widely assumed that such situations require control processes to ensure that the tasks are performed adequately. Because by definition working memory consists of information maintenance during task processing, these control processes are inherent to the cognitive architecture that implements working memory.

In some models of working memory, a dedicated system called the *central executive* is in charge of these control processes (e.g., Baddeley, 2000; Baddeley & Hitch, 1974; Cowan, 1999; Cowan, 2005; Engle, Kane, & Tuholski, 1999). Such a conceptualisation has many drawbacks, not in the least that it is a homunculus (e.g., Baddeley, 1996). Several attempts have been made to fractionate the central executive, by looking into separate executive functions (e.g., Burgess, 1997; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000), or by looking into even simpler executive control processes required to cope with task demands (e.g., Vandierendonck, Szmalec, Deschuyteneer, & Depoorter, 2007), such as input and output monitoring (e.g., Deschuyteneer & Vandierendonck, 2005a; Vandierendonck, Deschuyteneer, Depoorter, & Drieghe, 2008), response selection (e.g., Deschuyteneer & Vandierendonck, 2005b; Szmalec, Vandierendonck, & Kemps, 2005), memory updating (e.g., Kane, Conway, Miura, & Colflesh, 2007; Szmalec & Vandierendonck, 2007; Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011), and inhibition (e.g., Friedman & Miyake, 2004; Verbruggen & Logan, 2008).

Studies designed to clarify the executive processes or functions involved in working memory mostly use a dual-task methodology in which a second task overlaps the execution of a short-term memory task. Performance on both tasks is relevant. As working memory capacity is assumed to be limited, either task may suffer from the overlapping task execution, at least to the extent that both call on the shared resource. Thus, it may be expected that performance on the serial recall task is impaired when during any phase of the task, another task is performed that also taxes working memory (either in terms of storage or in terms of executive control processes). For example, if response selection calls on executive resources that are used to maintain information in working memory, then a concurrent task requiring response selection will impair memory performance (e.g., Szmalec et al., 2005; Vandierendonck, Kemps, Fastame, & Szmalec, 2004). Similarly, when a memory load competes with performance in an arithmetic task, performance on both tasks may be less than optimal (e.g., Imbo et al., 2007). Recently, also interest has risen in another type of procedure where tasks do not overlap, but require fast and flexible switching from one task to another. Because the previous task is no longer relevant, traces of the preparation and execution of the task may be left in working memory and can compete with preparation and execution of the present task. Interestingly, the kind of overlap in such a situation will be related more to executive control processes than to storage. The interest in the task switching paradigm was no doubt spurred by findings obtained with the Wisconsin Card Sorting Test in patients with frontal brain damage. In this test, cards displaying geometric figures must be sorted according to a particular rule that must be detected; when the rule is unexpectedly changed, these patients have difficulties in adapting their behaviour to the new rule. This observation indicates a lack of flexibility or a tendency to perseverate, i.e., to stick to the same task (Norman & Shallice, 1986). Even in healthy subjects, the requirement to switch tasks comes with a cost (Jersild, 1927; Kiesel, Steinhauser, Wendt, Falkenstein, Jost, Philipp et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). If it is indeed the case that working memory and flexible task switching both call on executive control, study of processes common to both should help to enlighten our understanding of executive control processes and, by extension, working memory. A critical issue therefore concerns the question whether task switching depends on working memory and whether taxing working memory would affect task switching performance.

Working memory and task switching

Task switching heavily relies on verbal working memory. This is a robust finding. On the one hand, it has been shown that the requirement to verbalise the task goals enhances task switching performance (e.g., Goschke, 2000). On the other hand, taxing verbal working memory, in particular the phonological loop in Baddeley's model, makes task switching more error prone and slower (Baddeley, Chincotta, & Adlam, 2001; Bryck & Mayr, 2005; Emerson & Miyake, 2003; Liefooghe, Vandierendonck, Muyllaert, Verbruggen, & Vanneste, 2005; Miyake, Emerson, Padilla, & Ahn, 2004; Saeki & Saito, 2004a; Saeki & Saito, 2004b; Saeki & Saito, 2009; Saeki, Saito, & Kawaguchi, 2006). These findings support the hypothesis that maintaining a verbal representation of the task goal in working memory helps to keep attention focused on the task at hand.

In contrast to these findings, other studies concerning the role of working memory in task switching are less unanimous. Logan (2004) compared the so-called task span to the memory span for task names. To that end, participants were requested to memorise a series of task names. Next, they were requested to apply the tasks in the same order to a series of targets that were presented at a slow pace. Subsequently, they were requested to recall all the task names in correct order. Logan varied the number of task names to be recalled and the difficulty of the application by varying the number of switches in the series. Consistently, Logan observed no systematic differences between the number of task names applied in the correct order (task span) and the number of task names remembered in the correct order (memory span). That led him to conclude that a single-resource working memory system cannot account for these findings. In a similar vein, Kane, Conway, Hambrick, and Engle (2007) compared task switching performance in subjects with a low and a high working memory span. They found that high-span subjects performed better than low-span subjects (faster, less errors), but working memory capacity did not interact with task switching performance (low spans did not show higher switch costs). Also other studies have confirmed this lack of relationship between working memory load and task switching (e.g., Kiesel, Wendt, & Peters, 2007; Logan, 2006).

Working within the time-based resource-sharing (TBRS) approach (Barrouillet, Bernardin, & Camos, 2004), quite different results were obtained by Liefooghe et al. (2008). The TBRS model assumes that central attention is a single unitary resource that is needed as well for refreshing the decaying working memory contents as for task processing. Consequently, when a series of tasks have to be performed during the retention interval of a serial memory task, the longer the tasks occupy central attention, the less time is left for refreshing working memory contents. Several studies have confirmed this implication of the model (e.g., Barrouillet, Bemardin, Portrat, Vergauwe, & Camos, 2007; Portrat, Barrouillet, & Camos, 2008). Liefooghe et al. (2008) reasoned that due to the task switch cost, when a series of tasks contain more task switches, attention will be occupied for a longer time than when there are fewer switches. Consequently, serial recall of the memoranda will be impaired more, when the ratio of task switches to task repetitions in the retention interval is larger. These expectations were completely confirmed by the results: (a) performance was worse when the retention interval was filled with only task switches compared to only task repetitions, (b) performance was also worse when the interval contained relatively more switches than when it contained fewer switches, (c) variation of the memory load from 3 to 8 memoranda did not change the pattern of findings and (d) task performance was not affected by the size of the load.

One particular procedure within the task-switching paradigm requires the participants to select the tasks themselves: in voluntary task switching (VTS) the participants are instructed to randomly alternate between a number of tasks (Arrington & Logan, 2004; Arrington & Logan, 2005). This procedure puts a higher demand on executive control processes during task switching because of the requirement to randomly select the tasks. Task switching performance in this procedure seems to be governed by the same top-down and bottom-up factors as in the other task-switching procedures (Arrington, 2008; Arrington & Logan, 2005; Arrington & Rhodes, 2010; Liefooghe, Demanet, & Vandierendonck, 2010; Mayr & Bell, 2006; Yeung, 2010). The most important innovation of the VTS procedure is that also task choice performance can be measured. This reveals a bias towards selection of more repetitions than switches. This bias is modulated by top-down as well as bottom-up factors (Vandierendonck, Demanet, Liefooghe, & Verbruggen, 2012). A few studies tested the role of working memory and executive control processes, and observed that the task-repetition bias depends on these processes (Arrington & Yates, 2009; Demanet, Verbruggen, Liefooghe, & Vandierendonck, 2010; Weaver & Arrington, 2010).

This brief overview of research on the relation between working memory and task switching reveals a very peculiar pattern of results. Some studies show an effect of working memory load on performance; some don't. Some studies show an effect of task switching on memory recall; some don't. Clearly, there are subtle interactions between working memory and task switching and this calls for an appropriate conceptualisation of the processes involved in order to account for this pattern of findings. In what follows, first the flow of executive control in flexible goal-directed task execution is discussed. Next, a model of working memory is presented that can account for at least some of the findings reviewed here. Finally, it is shown that this model can account for these particular findings.

Executive control in task execution

Consider a situation in which a person performs cued task switching to a series of targets. For the sake of this presentation, the targets are digits (0-9, excluding 5) and the tasks are magnitude (smaller or larger than 5) and parity judgment. On each trial, a cue indicating one of the tasks is presented and is followed by a task stimulus (target). The interval between the cue and the target (cue-target interval, CTI) can vary. Perception of the cue leads to retrieval of the task name from long-term memory (LTM). Preparations must now be made to perform the task.

The retrieved task name triggers implementation of a task set. According to Logan and Gordon (2001), a task set consists of the representation in working memory of a series of task parameters useful to the execution of a task. That means that a task set is responsible for orienting attention towards the relevant aspects of the environment, for applying the correct target categorisation rules, for applying the correct response mapping rule, etc. Hence, the task set biases attention towards the task-relevant elements in the environment and in working memory. The task set also biases processing towards the application of the task-relevant categorisation rules. In the context of the present example, this means that when the parity task set is being deployed, that parity categorisation rules become to be preferred over other target categorisation rules (such as magnitude categorisation rules, or form categorisation rules, etc.). The task set also biases processing towards the appropriate category-response mapping rules. Again, in the context of the parity task set, rules such as odd-left and even-right (or their reverse if the case applies) become preferred over other category-response mapping rules. Quite likely, this list of preparatory actions is not exhaustive (see e.g., Vandierendonck et al., 2010), but all these settings are necessary to avoid erroneous responding.

These preparatory actions are performed while traces of the previous task execution are still present, which means that task-set preparations have to overrule carry-over from the previous task (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000). Moreover, with shorter CTI durations, these preparatory actions may overlap with target processing. The target activates automatic action sequences such as stimulus-response associations (Pashler & Baylis, 1991) and stimulus-task associations (Gade & Koch, 2007; Waszak, Hommel, & Allport, 2004) formed during previous trials. When activated, these associations may compete with the preparations for a new task set. The question now is whether task preparation can shield the present task goal and task set from such bottom-up triggered processes, and if so how such shielding can be realised (see also Vandierendonck, 2010).

First, I consider the case where the *previous task set perseverates* (as in prefrontal patients, Norman & Shallice, 1986). This may be the case when it is expected that the next task will repeat or when something happens that results in maintaining the task set's strength (e.g., disengagement of the task-set at the end of trial was not done or was not successful). If the trial is a task-repetition trial, this is not problematic because the new and the old task set are the same. However, on a switch trial, the new task set will have to compete with the old one. Very likely, the old task set will be stronger than the present one. What then further happens, may vary from situation to situation. A first possibility is that the old task set maintains its strength and the new one remains weak. All biases go in the direction of the old task and with a high probability that task set will dictate the outcome of the trial, which may be either a correct response (on task-congruent trials, e.g., when the mapping rules of both tasks lead to the same response) or an incorrect response (on task-incongruent trials). The second possibility, is that the strength of the new task set grows rapidly so that this task set soon overpowers the old one. In that case, normally a correct task execution would be expected. Finally, the third possibility is that both task sets gradually become about equally strong and end up in a kind of deadlock in which neither of them wins. This either leads to a response that comes too late or to no response at all, because of the enduring competition and the unfinished task set preparation. When such a deadlock occurs, other bottom-up triggered processes may take over and still result in a response (see below).

A second case to be considered is when a previously formed *stimulus-response association* provides a short-cut to the response (Pashler & Baylis, 1991). Assume that task-set preparation is steadily going on. Very early in the preparatory process, the stimulus-response association is triggered. In the case of a stimulus repetition, this is an association that was formed or strengthened on the preceding trial. If this goes fast, the previously activated target, categorisation and response may still be present with some strength in working memory and if there are still traces around from the previous task preparation, all the elements are in place to produce a response, before preparation is finished. What actually happens in such a case, is that the bottom-up process wins and bypasses any intentions the person may have or may be putting in place.

The third and final case concerns triggering of a previously acquired *stimulus-task association* (Waszak, Hommel, & Allport, 2003). If the present target has been performed in the context of another task, the previous time it was presented (or even on more such occasions consecutively), the presence of the target triggers the association to the old task. If this is the same task as the present one, top-down preparation and bottom-up processes converge. If, however, the present and the triggered task are different, the situation is similar to that of the first case (perseveration of the old task set) and again the timing will determine the outcome.

Summarising, execution of a task is the result of preparatory processes on the one hand and bottom-up triggered processes on the other hand. Sometimes these processes converge resulting in faster responses and less errors; at other times these processes conflict and the result by and large depends on the time course of the two sets of processes.

A working memory model of executive control

Many theories of working memory share the assumption that short-term (working) memory consists of activated long-term memory contents. There is obviously an intricate relationship between short- and long-term memory, but it is necessary that the contents of working memory can be transformed, changed, combined, etc. in such a way that this does not have immediate consequences for the contents in LTM. Moreover, sometimes it is desirable to have two instances of a same entity (as in processing sentences like *Can you can a can as a canner can can a can?*). In order to achieve this, instead of having LTM entities activated, the working memory system needs to contain *instantiations* of information present in LTM (see also Logan & Gordon, 2001). In the present modelling, this is achieved by assuming that besides declarative information, LTM contains information in the form of condition-action rules, whereas working memory contains the consequences of the application of such rules to the already present working memory contents. For example, if working memory contains a cue to perform a magnitude judgment task, the LTM rule "IF a cue links to magnitude judgment, THEN load the task name 'magnitude' in temporary memory". The result of this application is that an instance of the task name is made available in working memory. When this element becomes more active during preparation and execution of the task, this has no direct effect on the content of LTM.

In addition to a storage of declarative information as in the example just given, the working memory system must also provide for *storage of information pertinent to task execution*. Typically, when a task has to be executed, one has to set one's mind to doing the task. This minimally requires setting up a task set, including stimulus-response categorisation and mapping rules. As an example, consider the LTM rule "IF the target is categorised as small, THEN emit a left response". Note that such a rule merely represents the experimenter's instructions in LTM. Treating such rule in the same way as the previous example would result in entering a symbol in working memory that a left response is needed. However, the left response is probably not needed immediately, but at a moment when all the conditions for emitting the response are met. This information clearly belongs to a control loop and is therefore stored as a rule in a dedicated executive memory subsystem of working memory[1].

Working memory is thus conceived as consisting of two subsystems, namely a declarative WM system (dWM) that contains instances which are currently needed to work on, and an executive WM system (eWM) that stores the task set and rules that are currently relevant for task execution. This distinction is similar to Oberauer's (2009; 2010) distinction between declarative and procedural working memory. In Oberauer's conception, working memory operates on three levels of representations. At the lowest level, the declarative working module consists of activated (declarative) long-term memory elements. A subset of these elements are directly available for operations, this is the area of direct access. Within this area one single representation is in the focus of attention. A similar stacking of layers is present in procedural working memory, which at the lowest level consists of activated procedural LTM. A subset of these elements constitutes the bridge (like the control centre on a ship) which consists of the procedures that are directly relevant for task exe-

1. Note that this proposal goes back to the initial conceptualisation of the central executive in the Baddeley and Hitch (1974) model, as a system that can call on storage facilities.

cution. The result of this processing is the selected response, the response focus at the highest level.

Even though there is a large similarity between the present modelling and the conceptualisation developed by Oberauer (2009), there are also some important differences. First, I prefer the label executive working memory because this links clearly to what has previously been called the central executive. Furthermore, the present modelling does not commit itself to a strict three-layer parallelism between the two subsystems. By storing a rule of the form “IF the target is categorised as ‘small’, THEN respond left” in a dedicated memory subsystem, on each cycle of processing, it can be checked whether the rule matches. This has the advantage that the rule is directly available when needed (which can be achieved during task preparation even before the relevant target is present) without a need to retrieve it from LTM. Finally, it was already pointed out that not activated LTM but LTM-based instantiation forms the basis of working memory representation in the present model.

Elements in both subsystems of working memory suffer from decay[2]. Explicit supportive actions are needed to keep the relevant elements active. One such mechanism is based on *binding* of information in dWM and is based on linking declarative working memory contents together on the basis of information available in executive working memory. For binding to succeed, a goal name must be sufficiently active in dWM and the corresponding task set must be dominant in eWM. Once this basis for binding is available, the goal can be bound to the present target, its categorisation, and the response. In other words, four dWM elements (goal, target, categorisation, response) are bound together as another dWM instance. Such binding can only occur when the corresponding task execution rule is sufficiently active in eWM. After realising the binding, the rule in eWM can be applied and response execution can start.

Another mechanism to counteract decay consists of *active refreshing* of dWM contents. This requires a memorisation goal that ensures proper reactivation of the decaying elements.

Most, if not all, working memory theories share the notion of limited capacity. So far, the impression may have been created that as a result of many instantiations, dWM becomes overpopulated with all kinds of instances varying in their degree of activation. There is indeed no limit on the number of instances that can be implemented. However, there is a limit to the total amount of activation of the instances. When this limit is approached, all instances, except active bindings and goal names, loose a proportion of their strength. This way, instances slowly fade away allowing for some form of recency or familiarity. A similar capacity limit governs eWM.

2. This assumption is also not shared by Oberauer (e.g., Oberauer & Lewandowsky, 2011).

Given this architecture and the dedicated mechanisms, how does this WM system operate to perform a task or to maintain information or even to do both at the same time? Each of these aspects (memorisation, task performance and their combination) occurs in the task-span procedure of Logan (2004), which was discussed in the introduction. This is used as an example to explain these modes of operation. Figure 1 (p. 239) displays a graphical example to elucidate the processes involved according to the present model. The explanation in the next few paragraphs will refer to this figure, among others to indicate the pathways involved, by referring to the numbered arrows in the figure.

First consider *information maintenance*. In a context of explicit learning or memorisation, the person has the intention to maintain the information in working memory for a while. To achieve this, a memorisation goal must be installed in working memory. The name of the goal becomes instantiated in dWM, and this triggers a rule to install the corresponding task set in eWM (pathway 1, in Figure 1). This task set controls acquisition, maintenance and recall of the memoranda in dWM (pathway 2). On presentation of a memorandum, it is instantiated in dWM. While the memorandum is in the perceived environment and also after the memorandum is no longer present, the task set will occasionally trigger processes to refresh, i.e., to reactivate, the instance. When recall is required, a recall cue will be instantiated and in the presence of this cue, the task set will supervise recall of the instances one by one. All these actions of the task set are governed by procedures stored in LTM that are automatically triggered when certain conditions are met.

Task execution occurs in a similar way. A cue (either external or internal) pointing to a particular task or goal is instantiated in dWM and triggers activation of the task name in dWM. This in turn leads to loading the task set in eWM (pathway 3). Further configuration of the task set includes setting of the relevant "parameters" and activating the relevant rules in eWM (pathway 6). When a target is detected, it is instantiated in dWM. As soon as it has acquired enough activation, it can trigger a previously learned target-response association or a categorisation rule resulting in an instantiation of a category name, such as "small" in the context of a magnitude judgment task (pathway 4). This chain of events can be biased towards the instances that fit the pre-activated rules in eWM (pathway 5). The category-name instance can trigger a response mapping rule such as "IF small THEN left", leading to instantiation of the response label. A dominant task set can at any time trigger the formation of a binding, in which the relevant and dominant goal, the target, the category and the response are bound together. Such a binding is shown in Figure 1 for the magnitude goal, target '4', category 'small' and response 'left' (these nodes are shown in grey). A binding that has been sufficiently activated can then match a prepared rule in eWM (pathway 7), which starts response preparation and execution.

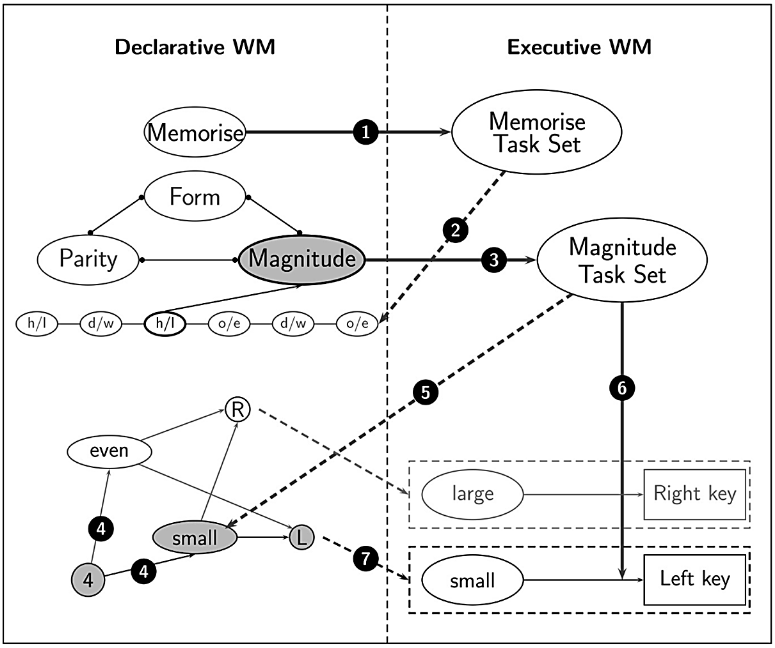

Figure 1

Schematic representation of the interaction between declarative and executive working memory in the task-span procedure of Logan (2004). First, for the memorisation phase, dWM contains the memorise goal, which activates the corresponding task set in eWM (pathway 1). This task set supervises maintenance of the memoranda in dWM (pathway 2). In this example, the memoranda are task names such as 'hi-low', 'digit-word', ... (the nodes h/l, d/w, ...). Under control of the memorise task set, these task names are recalled in correct serial order. The currently retrieved task name acts as a cue to activate the corresponding task goal (magnitude, in the example) resulting in lower degrees of activation of previously active task goals The activated goal in declarative working memory triggers configuration of the corresponding task set in executive working memory (pathway 3). When the current target is presented, it is instantiated in declarative working memory. The target is associated with the categorisation outcomes and responses of the recently applied tasks (pathway 4). The choice between the possible categorisation outcomes is biased toward the correct categorisation by the task set (pathway 5), which also preloads the allowable rules in executive working memory. A binding of the task goal (magnitude), the target (4), the categorisation outcome (small), and the response (L) occurs (shown by the grey filled nodes). This binding inputs to the response selection process shown at the bottom of the executive working memory module (pathway 7). These joint actions result in producing a response to the target, after which control switches back to the memorisation goal and task set. Pathways 1, 2, 3, 5, and 6 (dark grey lines) represent top-down process regulation (executive control).

The same figure also applies to explain *task execution under load*, or vice versa, *maintaining stored information while executing a task*. In this particular example, first a series of task names are memorised (as described above). Next, they are recalled one by one in serial order. Each recalled task name acts as a cue to activate the corresponding task goal. In Figure 1, it is shown how the third memorandum (high-low) activates the magnitude task name, which then results in configuration of the corresponding task set. This starts the complete chain of events for applying the task to the target meanwhile presented (4 in the example), and after correct execution, the response left is emitted. The important thing about this situation is that the two task goals "memorise" and "magnitude" are in charge in an alternation. First, the memorise goal supervises retrieval of the next task name, after which the magnitude task is triggered and takes over. The magnitude task goal and task set remain in control until the response is produced; after that control is transferred back to the memorisation goal.

This goal alternation is only possible by virtue of installation of a superordinate goal coordination that supervises this alternation. Figure 2 shows the goal structure that is needed to achieve this. At the top, a goal to coordinate memorisation and task processing is needed. In this particular case, this top goal places memorisation and task processing in an alternating chain, such that the memorisation takes over when task processing finishes by producing a response and vice versa, task processing takes over when the memorisation goal succeeds in recalling the next task name. The task processing goal itself is substituted by a series of subgoals related to the specific tasks that can be performed, namely magnitude, parity, or form judgment.

How is this hierarchical goal structure implemented in WM? First, the top-level goal (dual-task coordination) has to be present in WM all the time (for reasons of clarity not shown in Figure 1). The goal name is instantiated in dWM, and eWM contains the corresponding task set, inclusive the rules governing the alternation of the two subordinate goals. At least two rules seem to be necessary: one rule specifies that when a response is emitted from the task processing goal, a switch must be implemented towards the memorise goal, and vice versa, when the memorise goal is in control and the conditions are met, a switch towards the task processing goal is realised. In discussing the applications of the model to experimental data, more will be said about the conditions that allow such a switch. Anyway, the implication is that eWM simultaneously contains a dual-task coordination task set and one of the subordinate task sets. This is possible because the dual-task coordination task set, in fact, controls the subordinate task sets. The execution rules kept in eWM can exist together without creating competition between the two task sets (e.g., dual-task coordination and task processing) because their conditions do not overlap: the dual-task rules will become applicable when particular con-

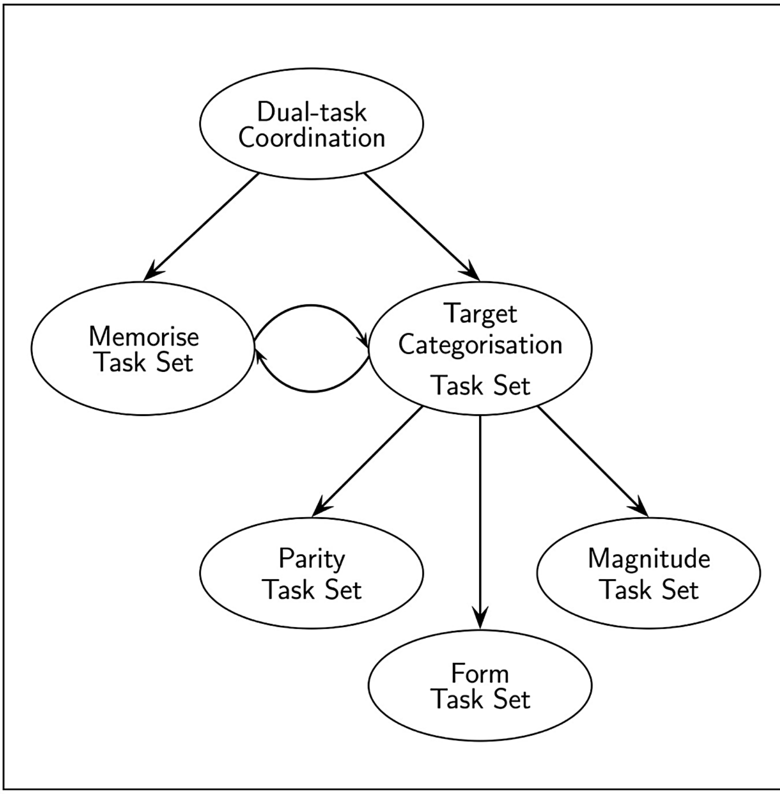

Figure 2

Representation of the goal structure and hierarchy of task sets involved in a dual-task coordination of a combined memorisation and processing demand. The graph displays the hierarchy of task sets which are needed to achieve the hierarchically coordinated task goals. The top of the hierarchy is a special task set that sets the tasks parameters for performing the two tasks in alternation depending on the task demands. On the second level, task sets are represented for the memorisation demand and for the target categorisation demand. The interchange arrows at this level show the alternation between these two goals. Note that the target-categorisation task set is itself a coordinating task set that allows switching between two or more other goals and their corresponding task sets.

ditions are met that do not constitute an input for the subordinate task rules. The dual-task rules will typically respond to the presence of conditions that indicate that a switch from one subgoal to another is possible or desirable, whereas the subgoal rules will rather respond to the presence of memoranda, targets, cues, or task names.

Application to task switching under load

After having specified a working memory model capable of storing and maintaining declarative information and also capable of representing information directly relevant to task execution, the model can now be applied to task switching under a WM load. The question addressed here, is whether the model is capable of accounting for findings as different as those obtained in the task-span procedure (Logan, 2004; Logan, 2006) and those based on the time-based resource-sharing methodology (Liefooghe et al., 2008) that were discussed earlier in this article. These experiments all studied task switching under a memory load, but differ from each other in a number of respects: (1) whereas the task-span procedure uses a working memory load that is relevant to task execution, the TBRS methodology works with a task-irrelevant memory load; (2) in contrast to the slow execution of the series of tasks in the task-span procedure, the experimenter imposes strict time constraints on execution in the TBRS method. Can the model account for differences in findings on the basis of such procedural differences?

Application to task-span procedure

As already explained, the hierarchical goal alternation structure as displayed in Figure 2 is needed for performing task switching under a working memory load. What then happens in WM is shown in Figure 1. In a first phase of the task-span procedure only the memorisation goal is need, to load the list of memoranda – task names – in working memory. After the task names have been loaded, the second phase requires the alternating goal structure to retrieve the next task name. Each cycle of this alternation starts with the presentation of a target, which acts as a signal to retrieve the next task name. When the task name has been retrieved, control transfers to the target categorisation goal. The task name is used to cue the corresponding goal which gets instantiated in dWM and which leads to configuration of the task set and its categorisation/mapping rules. Figure 1 shows retrieval of the third task name, which cues the magnitude categorisation goal. Meanwhile also the target is instantiated in dWM and it activates associations with categorisations learned previously. Also on the basis of prior learning, associations with the response keys are triggered, resulting in an instantiation of the response names in dWM. These bottom-up processes usually activate instantiations that can lead to correct responding as well as instantiations that lead to incorrect responding. The top-down processes resulting from the presence of the task set, lead to binding of the task goal (magnitude) with the target (4), its categorisation (small), and the mapped response (left). The binding matches the small-left rule in eWM and response preparation and execution follows. After the response has been emitted, the next target appears and the next cycle begins. Given the slow pace of the procedure in which the target remains present until a response is emitted with any constraint, even when the target is already present, the time can be taken for the memorisation goal to refresh the list of task names in dWM, before retrieving the next task name for further action.

When all the targets have been processed, the third stage starts which only requires the memorisation goal, to recall the list of task names. Given that the task names have been recalled in the previous phase and have thus been refreshed and in view of the opportunities to refresh the list of tasks at the end of each task cycle in the second phase, the list of names recalled now, will quite likely be the same as the list of names recalled during the second phase, give or take a few rare differences. This also holds for the counterbalanced condition in which the memory span is recorded before the task span.

In short, this modelling accounts for the findings that have been reported for the task-span procedure. The main reason for this account is that the entire procedure allows sufficient time to rehearse or refresh the memorised list. The number of instances that can be remembered in the correct order also depends on the capacity of dWM to maintain serial information and the ability to form chunks. This capacity limit governs the retrieval of the task names in the task execution phase as well as in the recall phase at the end. For that reason, the only factor that matters is the availability of time to rehearse.

Application of the task-span procedure has also shown that difficulty of the series of tasks does not matter much. Performance is quite similar whether there are no, few, or many task switches in the series. It is well known that task switches are more difficult than task repetitions (in terms of slower responding and more errors). However, this does not matter in the task-span procedure because after execution of a task switch (which may take typically 100-150 ms longer) as much time for rehearsal is available than after a task repetition.

Application to TBRS

Although the general situation is quite similar in the TBRS applications, the two procedural differences mentioned above, result in a quite different situation for the usage of WM resources. Consider, the third experiment reported by Liefooghe et al. (2008). On each trial, first a series of 3-8 letters were presented for later recall. Each letter was shown during 1500 ms followed by a 300 ms empty interval. Next, during a 9600 ms interval, 8 targets were presented one at a time for 900 ms followed by a 300 ms blank period. The targets were digits 1-9, excluding 5 to which a parity or a magnitude task was applied depending on whether the letter was blue or red, respectively. In half of the trials, the series of tasks in the interval contained few (2-3) task switches; in the other half, the series of tasks contained many switches (5-6). The results of this experiment were that letter recall was better, irrespective of list length, on the trials with few (.78) than on the trials with many (.75) switches, but performance decreased with list length. As was expected, the times spent on the digits were longer on the trials with few (725 ms per task) than on the trials with many switches (770 ms). Thus, 64% of 9600 ms interval was occupied by task processing in the condition with many switches compared to 60% in the condition with few switches. Also more errors were produced on the mixed trials (0.23) than on the pure trials (0.17). An analysis of task switching performance, excluding errors and tasks following an error yielded performance averages of 656 ms on task repetitions and 725 ms on task switches. These averages were not affected by list length and the two factors did not interact.

Figure 3 (p. 245) exemplifies the operation of the WM model in its application to this TBRS experiment. As each trial starts with uploading the memoranda, first the memorisation goal is set up (pathway 1) and supervises instantiation and strengthening of these memoranda (pathway 2). Thereafter, the task processing block starts with the presentation of a coloured target. This stimulus event is encoded as a target (the value 4) and its colour (red) which is the cue to performing the magnitude task. This results in instantiating the magnitude task name (pathway 3) and the corresponding task set (pathway 4). Meanwhile the instantiated target triggers applicable rules from LTM leading to instantiations of categorisations 'small' and 'even' (pathway 5) and instantiations of the response names 'left' and 'right'. Further configuration of the magnitude task set results in implementing the mapping rules in eWM (pathway 7) and the task set also biases the dWM instances by installing a binding of the goal, the target, the correct category and the response (pathway 6). Finalisation of this binding inputs to the relevant response rule in eWM (pathway 8). Once the response is emitted and as long as no new target is presented, control is switched to the memorisation task goal for refreshment of the memoranda. This goes on until a new target appears at which time, the condition is met for transferring control back to the task processing goal.

This account reveals three differences with the sequence of events as they occur in the application to the task-span procedure. First, in the present situation an external cue is present whereas in the task-span procedure the task name was retrieved from the previously learned list. Second, in the TBRS procedure the time allowed for responding is limited, which implies that after giving a rather fast response, there is a limited time for rehearsal; this time ends when the next target appears. Continuation of rehearsal when the next target is presented may result in poor performance on the digit categorisation task. Thus, the amount of time available for refreshing the memoranda is lim-

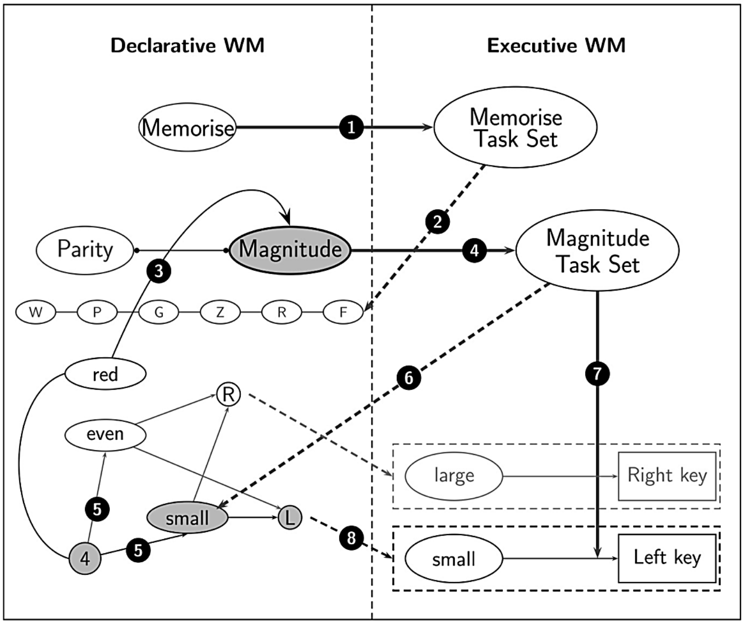

Figure 3

Schematic representation of the interaction between declarative and executive working memory in the TBRS study of Liefooghe et al. (2008). First, for the memorisation task, dWM contains the memorise goal, which activates the corresponding task set in eWM (pathway 1). This task set supervises maintenance of the memoranda in dWM (pathway 2). In this example, the memoranda are consonants (the nodes W, P, G, ...). The memorise task set is also responsible for recall of these memoranda in serial order, at the end of a trial. When the target is presented (a coloured digit), it is instantiated in dWM as a value (4 in this example) and as a cue (red). The cue triggers retrieval of the task name 'magnitude' (pathway 3) which is then instantiated as the goal in dWM. This results in lower degrees of activation of previously active task goals. The activated goal in declarative working memory triggers configuration of the corresponding task set in executive working memory (pathway 4). The current target is associated with the categorisation outcomes and responses of the recently applied tasks (pathway 5). The choice between the possible categorisation outcomes is biased toward the correct categorisation by the task set (pathway 6). The task set also preloads the allowable rules in executive working memory (pathway 7). A binding of the task goal (magnitude), the target (4), the categorisation outcome (small), and the response (L) occurs (shown by the grey filled nodes). This binding inputs to the response selection process shown at the bottom of the executive working memory module (pathway 8). These joint actions result in producing a response to the target, after which control switches back to the memorisation goal and task set. Pathways 1, 2, 4, 6, and 7 (dark grey lines) represent top-down process regulation (executive control).

ited and is a bit longer when the sequence of tasks contains few switches than when it contains many switches. The model predicts this difference because on switch trials a new task set must be configured and the carry-over from the previous task execution can interfere with present task execution. On repetition trials, the previous task set remains valid and carry-over may prime the correct response. Consequently, the time left for refreshment of the memoranda is smaller in the condition with many switches. This results in some loss of information and slightly poorer recall in the condition with many switches. As the time available for refreshment does not vary with list length, it follows that relatively more information will be lost at longer list lengths resulting in poorer recall at longer list lengths. A third difference concerns the irrelevance of the memoranda to task processing. Because of this, the memoranda do not have to be recalled during task performance and hence the task execution itself does not provide the occasion for refreshing the memoranda.

Conclusion

Application of the model to these two experiments reveals that a single model can account for the contrasting findings in these experimental conditions. The main element in this explanation concerns the difference in time control in the two experiments. While the activities of the model are basically the same in both applications, the only difference concerns the time available for refreshing the memoranda. With less time, recall performance suffers and when there is no shortage of time to rehearse, recall performance does not depend on the difficulty of the tasks being performed. Indeed, the difficulty of a task switch, or any other form of task difficulty, has no direct effect on the instantiated memoranda. There is only an indirect effect by virtue of preventing rehearsal of all the memoranda.

Discussion

The model presented here elaborates the general idea that working memory is a workspace for storing and manipulating temporary information. To achieve this, such a model must provide storage space for information and the means for keeping some of this information active, and it must also provide the means for controlled task execution. In this sense, this model is a true descendent of the original model of Baddeley and Hitch (1974), in that it provides both a space for storage[3], and facilities for task execution (the central

3. This storage space in the present model corresponds to the phonological loop and the visuo-spatial sketch pad in the original model, but bears more similarities to the episodic buffer in later versions of the model (Baddeley, 2000).

executive in the original model). While the central executive has all the features of a homunculus, in the present model, eWM is just a mechanism that temporarily maintains task sets and task rules to allow their interaction with the instances in dWM. No homunculus is lurking in the background.

Another difference with the original model is that the present model does not pronounce a distinction between verbal and visuo-spatial working memory. Though this distinction is important and is supported by an already impressive body of evidence (for a state of the art, see Vandierendonck & Szmalec, 2011), it was decided not to complicate the model with processes and distinctions that are not necessary for the present discussion. Nevertheless, it is also important to note that the phonological loop is a different kind of system from declarative WM as described in the present model and in the model of Oberauer (2009). The phonological loop may be considered as a low-cost support system for working memory. This is at least the picture that emerges from a few recent studies (Camos, Lagner, & Barrouillet, 2009; Camos, Mora, & Oberauer, 2011).

The model presented here is not one of a kind. As already mentioned the two-system conceptualisation owes a lot to the work of Oberauer (2009; 2010). The model can also be considered as a process implementation of the TBRS model (Barrouillet et al., 2004), although it is not identical to that model. The TBRS model makes a number of assumptions that are not shared in the present model. For example, the present model does not assume that central attention is an all-or-none resource, or that rapid switching occurs between maintenance and processing. Actually because of the latter assumption, the TBRS model predicts recall to be directly related to the amount of time available for rehearsal. The present model, on the contrary, assumes that switching between memorisation and task processing has a (switch) cost because both are tasks in their own right. As a consequence, the present model predicts that recall performance is also affected by the time needed to switch between task processing and memorisation. When conditions are compared with an equal number of tasks, this does not matter, but consider the situation where the two conditions contain a different number of tasks. In the first condition, a series of memoranda is stored and in the retention interval four very difficult tasks have to be performed (e.g., tasks requiring a response time of 800 ms), while in another condition eight easy tasks are performed (e.g., requiring 400 ms response time). In terms of occupying central attention as conceptualised in TBRS, the situations are completely equivalent: the tasks in the two conditions occupy attention for exactly the same time. The present model assumes a switch cost. If the switch cost is about 100 ms (a rather typical value), then the time available for rehearsal will be different in the two conditions: when there are only four tasks, the switch cost consumes an additional 400 ms, but when there are eight tasks, an additional 800 ms are consumed. Hence the present model predicts poorer recall in the condition with more tasks. Actual testing of this prediction may be difficult because of the large difference in processing time required for the two tasks and also because the cost of switching between memorisation and task performance might be smaller due to a smaller degree of overlap between the task sets.

Further work with the model is being performed. One interesting avenue is to study how working memory is involved in task selection in the voluntary task switching procedure. Instead of looking at task performance, this procedure allows to investigate how working memory loads affect task choice (Demanet et al., 2010; Weaver & Arrington, 2010). Additionally, implementation of a formal version of the model would further add to its value as a scientific tool.

I hope the more formal approach to working memory theorising adventured in the present article is more convincing to my dear colleague Géry d'Ydewalle. At least, I hope I have succeeded in convincing him of the usefulness of the working memory hypothesis and of its contribution to our understanding of cognition and intentional action.

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