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DECLARATIVE AND PROCEDURAL WORKING MEMORY: COMMON PRINCIPLES, COMMON CAPACITY LIMITS?

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Working memory is often described as a system for simultaneous storage and processing. Much research – and most measures of working-memory capacity – focus on the storage component only, that is, people's ability to recall or recognize items after short retention intervals. The mechanisms of processing information are studied in a separate research tradition, concerned with the selection and control of actions in simple choice situations, dual-task constellations, or task-switching setups. Both research traditions investigate performance based on representations that are temporarily maintained in an active, highly accessible state, and constrained by capacity limits. In this article an integrated theoretical framework of declarative and procedural working memory is presented that relates the two domains of research to each other. Declarative working memory is proposed to hold representations available for processing (including recall and recognition), whereas procedural working memory holds representations that control processing (i.e., task sets, stimulus-response mappings, and executive control settings). The framework motivates two hypotheses: Declarative and procedural working memory have separate capacity limits, and they operate by analogous principles. The framework also suggests a new characterization of executive functions as the subset of processes governed by procedural working memory that has as its output a change in the conditions of operation of the working-memory system.

Throughout his career, Andre Vandierendonck has worked on a better understanding of the limits of human cognitive capacity. Among other things, he has a long-standing interest in the operating principles of working memory and of executive functions. Both concepts play an important role in determining the success of our cognitive endeavours. The concept of working memory derives from the older concept of a short-term memory store, and due to this heritage, working memory is often described as a system for the short-term storage and processing of information. Both the storage capacity and the processing capacity of working memory are thought to be limited. The limited storage capacity is most apparent when people are asked to remember new sets of items (e.g., lists of words, arrays of objects) that are briefly presented to them for immediate recall or recognition. Accuracy in such tasks declines sharply as the set size of memory items increases, leading some researchers to estimate the storage capacity of working memory to about four items (Luck & Vogel, 1997; Cowan, 2001). The processing capacity of working memory is more difficult to grasp, and has therefore attracted less systematic research. Inspired by the work of Baddeley (1986), the processing side of working memory is often conceptualized as a “central executive” or, more recently, as a bunch of executive processes. However, as Vandierendonck, Deschuyteneer, Depoorter, and Drieghe (2008) have noted, the term “executive processes” remains vague, and no consensus has yet emerged on what belongs to the set of executive processes.

In the meantime, much research in the field of action control has begun to identify mechanisms and limitations of processes that are summarized under the umbrella term of executive functions, among them task switching (Monsell, 2003; Vandierendonck, Christiaens, & Liefooghe, 2008), dual-task processing (Pashler, 1994; Vandierendonck, De Vooght, & Van der Goten, 1998), response selection (Szmalec, Vandierendonck, & Kemps, 2005), and response inhibition (Logan & Cowan, 1984; Verbruggen, Logan, Liefooghe, & Vandierendonck, 2008). This line of research makes occasional references to a role of working memory in action control. For instance, Vandierendonck, Deschuyteneer, et al. (2008) argued that executive control depends on maintaining a task set in working memory. A task set is the set of representations and parameter settings that determine selection, monitoring and control of actions in the service of a goal. If such representations must be held in working memory for successful executive control, then research on working memory should have something to say about executive control. Specifically, the principles and mechanisms discovered by studying how people remember lists of digits or words over short periods of time should be similar, maybe identical to those employed when a task set is held available for some time to control cognition and action. Conversely, insights from work on executive control that addresses how task sets are maintained in working memory might also apply to how other information is maintained in working memory. This is the hypothesis I want to explore in this chapter.

I will propose a new theoretical framework for how the “storage” and the “processing” aspects of working memory relate to each other.

Let me start with an assumption that some might find surprising: Working memory is not a memory. Rather, working memory is an attentional system. By attention I mean any mechanism or process that prioritizes a subset of representations over others, thus giving the selected set of representations a larger influence on further cognitive processes. The term attention is usually reserved for the prioritization of perceptual input, but there is no reason other than the pragmatics of experimentation to limit it in that way. Already William James’ famous quote alludes to a more encompassing concept: “Everyone knows what attention is. It is the taking possession by the mind in clear and vivid form of one out of what seem several simultaneous objects or trains of thought.” (James, 1890, Vol 1, 403-404). I think of working memory as attention directed to memory representations, selecting at any time a small subset of our episodic memories and of our knowledge as the current content of our train of thought. Short-term maintenance of new information, which has been studied extensively in the working-memory literature, is a side-effect of paying attention to episodic representations of recent events (e.g., the random list of words read to us in an experiment), thereby preventing them from being quickly discarded at the expense of other, more interesting thoughts.

One consequence of this redefinition of working memory, which follows Cowan (1995), is that it does not matter much whether the contents of working memory are new information – as in a typical experiment on immediate recognition or recall – or information already well known to the person. The same mechanisms are engaged, and the same principles apply, in both cases (preliminary empirical support for this claim is offered by Oberauer & Risse, in press). This is important for my purpose because research on working memory primarily investigates how well people can remember and manipulate sets of items that are novel to them, whereas in typical experiments on executive control the information to be held in working memory (e.g., the necessary task sets) is given at the beginning of the experiment and learned reasonably well during the practice trials.

Working memory makes representations that are relevant for the current task or goal available for processing. Thinking and acting requires two kinds of representations, declarative and procedural. Declarative representations are those that provide information about the world, including information about the present state of the (external and internal) environment, memories of past events, and knowledge of facts. This information is represented in a format that can be flexibly used, among other things, for communicating it (that is why it is called "declarative"), by drawing inferences from it, and by manipulating it through cognitive operations. Procedural representations are those that guide cognitive operations and overt actions by specifying what is to do under which circumstances (where circumstances are given through declarative representations). Procedural representations can be explicated as condition-action rules, with the condition describing the circumstances to which the procedure applies, and the action component describing what is to be done (i.e., the cognitive operation or the physical action to be carried out). Although communicating procedural representations (e.g., when instructing people) requires translating them into a declarative format, such as a verbal rule or a graph, they are not themselves declarative: A core assumption of theories distinguishing declarative and procedural representations is that cognition and action is controlled by procedural representations, and declarative representations such as instructions must first be interpreted by procedures that take them as input and generate (cognitive) actions as output.

The distinction between declarative and procedural representations has been fruitfully applied to models of long-term memory such as ACT-R (Anderson & Lebiere, 1998). When working memory is conceptualized as attention to memory, as I propose, a natural consequence is to apply the distinction of declarative and procedural representations also to working memory. The contents of declarative working memory are those representations in declarative long-term memory that we currently pay attention to, so that we can use them for cognitive processes. The contents of procedural working memory are those procedural long-term memory representations that we currently pay attention to, thereby selecting them to guide our ongoing thoughts and actions.

I will argue that declarative and procedural working memory are two separate sub-systems that have analogous structures and operate by analogous principles (Oberauer, 2009). Declarative working memory is a sub-system for temporarily holding declarative representations available. These representations form the contents of thought, they are the objects of information processing. Procedural working memory temporarily holds procedural representations available that govern the cognitive operations we carry out on the declarative representations. Traditional research on working memory has focused mainly on declarative working memory by asking how we can briefly maintain sets of digits, words, or objects. Manipulation of these contents has been acknowledged as an important aspect of working memory, but the question how these processes are carried out and controlled has not taken center stage. The capacity limit of working memory is usually conceptualized in terms of how much information can be remembered, not in terms of a limit on information processing (for a review see Cowan, 2005). The procedural part of working memory has been investigated in research on action control. This literature has investigated the selection of (cognitive or overt) actions, the selection and scheduling of tasks, and the structure of the representations involved in these processes, which are often referred to as task sets. This line of research has also uncovered limitations of our abilities to select and control actions, most notably a severe constraint on how many cognitive operations can be carried out at the same time (Pashler, 1994). I will argue that the limitations on the “working” side of working memory are analogous to those on the “memory” side: We can usually carry out only one cognitive operation at a time because the capacity of procedural working memory is limited so that under most circumstances it can hold only one task set at a time.

The Structure of Working Memory

Declarative and procedural working memory serve the same general function – providing selective access to representations relevant for (cognitive) action. Thus, they encounter the same problems, and it is plausible to assume that these problems are solved in analogous ways in both subsystems.

The first problem to be solved is to make relevant representations available quickly, setting them apart from irrelevant representations. Anderson and Lebiere (1998) have proposed that representations in long-term memory are at any time activated to a degree that reflects their likelihood of becoming relevant soon, given the information currently held in working memory (called "goal focus" in that version of ACT-R). The implicit coding of expected relevance by activation becomes possible by rapid spread of activation along a network of associations, the strength of which corresponds to the conditional probability that the receiving element will be required, given the sending element is being used. The more active a representation, the easier it is to retrieve it. Thus, activation is the first stage of a representation's selection for action, and we can characterize the *activated subset of long-term memory* as the first, most encompassing component of the working-memory system. It contains both declarative and procedural representations, which I assume to be related through learned associations in long-term memory. Evidence for such associations comes from studies demonstrating that people acquire associations between stimuli (i.e., declarative representations) and task sets (i.e., procedural representations) that are applied to them (Waszak, Hommel, & Allport, 2003).

The second problem to be solved is that flexible cognition requires rapid reconfiguration of the representations guiding thought and action. When we reason through a problem, we build new structures of declarative representations to represent new configurations of entities – for instance, mental arithmetic generates new multiple-digit numbers; logical reasoning generates new mental models of possible states of affairs, and causal reasoning generates new hypotheses about causal connections between events or between variables. Likewise, flexible action requires reconfiguration of procedural representations. People can switch between tasks rapidly and implement new instructions, thereby responding to a stimulus or a situation in a way they never responded to it before, even working against a deeply ingrained habit – doing so is not easy but it is possible, and it requires a working-memory system that does not only retrieve what has been learned from long-term memory, but also enables the construction and temporary maintenance of novel structures. This problem can be solved by a mechanism for temporary bindings between representations. Temporary bindings differ from associations in long-term memory in that they can be established and disbanded quickly, whereas associations are learned (and unlearned) gradually through accumulation of small changes.

Temporary bindings serve to link representations into new structures. For declarative memory, I assume that there is a mental coordinate system, or mental space, in which content elements (such as digits, words, objects) are bound to places, so that they are related to each other by virtue of their relations in mental space. Elements bound to places in the mental space can be directly accessed through these places as cues. For instance, the information given by “Lisa went out for dinner while John was at the cinema. John was at the cinema before he attended the pop concert” can be interpreted by binding representations of Lisa and John to different places in a two-dimensional coordinate system with one dimension serving to distinguish different locations (restaurant, cinema) and the other representing time. Such a mental model automatically represents the non-stated fact that Lisa went out for dinner before John attended the pop concert, a fact that people can easily infer in a reasoning task (Vandierendonck & De Vooght, 1996). The elements forming a structure in mental space at any time constitute the content of a second component of declarative working memory, called the *region of direct access*. Memory lists, which are so often studied as the contents of declarative working memory, are a special case of structures assembled in the direct-access region by binding successive list elements to successive locations on one dimension of mental space.

On the procedural side, task sets are established by forming bindings between representations of relevant aspects of the world and responses to them (sometimes referred to as stimulus-response bindings). For instance, the instruction “Press the left button whenever you see a triangle or a circle, and press the right button whenever you see a square or a cross” can be interpreted by binding representations of the categories “triangle” and “circle” to a representation of the response category “left”, and binding the representations of “square” and “cross” to the response category “right”. The set of stimulus-response bindings established at any moment constitutes the content of a second component of procedural working memory, which I call the *bridge*.

The direct-access region and the bridge are the second components of declarative and of procedural working memory, respectively; they select a subset of the representations in the first component, the activated subset of long-term memory. This subset is directly available for processing. Declarative representations in the region of direct access can be accessed through their bindings to places in the coordinate system that act as cues. For instance, we can ask “what happened before the pop concert?” and thereby guide the focus of attention first to the pop concert in our mental model of the above-mentioned events, and then direct it away from there along the time axis in the direction of earlier events, where it will encounter the representation of John at the cinema. Analogously, representations of responses that are bound into a task set currently held in the bridge are directly available through their bindings to the corresponding stimulus categories. For instance, if the mapping from “triangle” to “left” is held in the bridge, any representation of a triangle that enters declarative working memory will directly elicit a movement toward the left response button. Thus, the task set (or sets) currently held in the bridge act as a “prepared reflex” (Hommel, 2000): Once set up, representations matching the template for the stimulus categories automatically trigger the selection of the response category bound to it. Like a memory list or a mental model that can be composed in declarative working memory quickly, a new task set can be established in procedural working memory rapidly, as shown by experiments of Cohen-Kdoshay and Meiran (2009) who demonstrated that a new task set acts as an automatically executed prepared reflex already at the very first trial following instruction.

The capacity limit of working memory arises primarily from a limit on the number of simultaneous bindings that can be established in the direct-access region and the bridge. This limit constrains the complexity of structures that can be formed in declarative working memory, such as lists or mental models, and the complexity of structures in procedural working memory such as task sets and action plans.

The third problem to be solved for a working-memory system is to make unambiguous selections of individual representations for processing. I already mentioned above the third and narrowest component of declarative working memory, the *focus of attention*. The focus of attention selects at any time one element out of the set of elements currently held in the region of direct access. For instance, the focus could select the representation of John at the cinema within the mental model from our example, and could move from there along the time axis toward the future to find out what John did after the movie. In general, the focus of attention serves to selectively access one element out of several elements currently held in the direct-access region. Much research has been carried out on this selection function using numerical tasks, beginning with Garavan’s counter task (Garavan, 1998) in which participants are asked to keep a running count of two categories of objects (e.g., circles and triangles). The time to increment a counter was found to be longer when the current counter differed from the one updated in the preceding step (e.g., a triangle following a circle, or a circle following a triangle) than when the same counter as before was updated again. Analogous switch costs between elements in working memory have been observed with arithmetic updating tasks (Kessler & Meiran, 2006; Oberauer, 2003) and spatial updating tasks (Kübler, Murphy, Kaufman, Stein, & Garavan, 2003). Switch costs of about the same magnitude are also found when numbers in working memory only need to be accessed as input for arithmetic computations but are not updated (Oberauer, 2003). These so-called object-switch costs indicate that the mental object last used for a cognitive operation has a special status of increased accessibility that carries over into the next processing step. I assume that this reflects the fact that the object was selected for processing by the focus of attention, and remains in the focus of attention until it is replaced, a process that takes time.

An analogous selection problem occurs on the procedural side: When more than one response alternative is bound to a corresponding set of situations or stimuli in the bridge, as is typically the case for a task set implementing instructions for a choice task, one of the response alternatives must be selected to be carried out. This selection, I assume, is accomplished by a *response focus* that holds one response representation at any time, thereby giving this representation a privileged status that marks it as the response to be executed. Selection of one response over its alternatives is necessary only until the response is executed. Nevertheless, in analogy to the focus of attention in declarative memory, which seems to hold on to the last object selected for processing even after processing is completed, I speculate that the response focus maintains the last selected response even after it has been executed.. This should facilitate repeating the same response over changing to a different response alternative in the next step. There is indeed evidence for response repetition benefits in successive speeded choice tasks (Bertelson, 1965), analogous to the object-repetition benefit (or object-switch cost) on the declarative side, although more recent research paints a more complicated picture, as I'll explain below.

In what follows I will explore two speculative hypotheses about the relation between declarative and procedural working memory. One is that the two sides of working memory are structured in an analogous fashion, as outlined above, and that they operate in analogous ways. This assumption leads to the expectation of analogous empirical signatures of the structure and the operating principles of declarative and of procedural working memory (see Table 1). My second hypothesis is that declarative and procedural working memory are different sub-systems which have separate capacity limits. This assumption leads to the expectation that loads on declarative working memory don't interfere with procedural working memory and vice versa, and that performance measures of declarative and of procedural working memory are not highly correlated.

Analogous Structure and Processing Principles?

Activated Long-Term Memory

The main role of long-term memory for working memory is to hold representations activated so that they are easy to retrieve when needed. Research on declarative working memory has shown that sets of items not currently needed can be quickly outsourced from the direct-access region into activated long-term memory, and retrieved back into the direct-access region when needed at a later point (Oberauer, 2002; 2005). The evidence for this process comes from set-size effects on reaction times: The size of a memory set affects reaction times of ongoing cognitive processes only as long as it is held in the region of direct access. An analogous process of rapid outsourcing and retrieval appears to happen during task-set switching. When people must switch from trial to trial between two or more task sets, they hold only the task set currently relevant for the upcoming trial in the central component of procedural working memory, the bridge, while maintaining the other task sets activated in long-term memory so that they can rapidly be retrieved into the bridge when necessary. Evidence for the assumption that task-set switching involves retrieval of a new task set from (activated) long-term memory comes from the finding of Mayr and Kliegl (2000) that switch costs were increased when the task to be switched to involved retrieval from episodic long-term memory, as predicted on the assumption that two processes of long-term memory retrieval interfere with each other. Relevant evidence also comes from the study of Rubin and Meiran (2005) on so-called mixing costs. Mixing costs reflect the difference in reaction times between single-task blocks in which only one task set is used for all trials in a block, and mixed blocks in which people must alternate between two or more tasks. Rubin and Meiran found that mixing costs did not increase when the number of task sets involved in a block was increased beyond two, contrary to what would be expected if all task sets used in a mixed block were held in a capacity-limited component of working memory. Further evidence along the same lines comes from a study by Kessler and Meiran (in press). They asked participants to switch between two main tasks (classifying objects by shape or color), and in addition to prepare for 0, 1, or 3 further tasks (classifying digits) that had to be carried out on 25% of trials. Reaction times on the two main tasks were unaffected by the number of additional digit-classification tasks that people had to prepare for, indicating that the additional "task-set load" did not compete for limited capacity with the currently relevant task set.

One prediction that follows from the analogy between memory lists and task sets is that set-size effects in procedural working memory, like those in declarative working memory, should be found only for task sets held in the bridge, but not for task sets activated in long-term memory. It is well established that reaction times increase with the set size, that is, with the number of stimulus-response mappings of the currently relevant task set. No study has yet investigated set-size effects of the currently irrelevant task set in a task-switching paradigm. Indirect evidence comes from a study by Hübner, Kluwe, Luna-Rodgriguez, and Peters (2004). They asked participants in one experiment to switch between a task with two and another task with four stimulus-response mappings. In a further, otherwise identical experiment people switched between two tasks, both of which had four stimulus-response mappings. Reaction times did not differ between experiments when the currently relevant task involved four stimulus-response mappings, suggesting that it makes no difference whether the currently irrelevant task set involves two or four mappings.

Activation of representations in long-term memory can make available only information that is represented in a unified fashion, because only unified representations can be thought of as carrying activation. For instance, when we receive information about a new constellation of known elements, such as "the church is one block east of the post office. The train station is two blocks north of the church. The police station is one block south of the train station", listening to these statements will automatically activate representations of the concepts involved (i.e. "church", "post office", etc.), but there is no representation of the constellation as a whole (i.e., a mental map of the layout described) in long-term memory to be activated. The same holds for a memory list of known items in a new, arbitrary order such as "blue, yellow, pink, brown, red". Activation in long-term memory can maintain the elements but not their relations. A representation of the structure can be assembled through temporary bindings in the region of direct access. Once that is accomplished, however, the working-memory system must avail of a mechanism for rapidly forming a new unitized representation of the structure. Without such a mechanism it would not be possible to outsource ordered sets of elements into activated long-term memory and bring them back later. Therefore, I assume that for every structure build in the direct-access region a new unitized representation or chunk is formed in long-term memory automatically. This chunk can be maintained active while the structure is removed from the direct-access region, and at a later point the chunk can be unpacked to re-establish the structure again in the region of direct access.

Evidence for the assumption that lists are maintained in long-term memory as chunks, and retrieved as chunks, comes from the finding that the time for retrieving a list from (activated) long-term memory is independent of the length of the list (Oberauer, 2005; Wickens, Moody, & Dow, 1981). Further evidence for the automatic formation of unitized chunks from lists held in working memory comes from experiments on the Hebb effect. The *Hebb effect* refers to the finding that immediate serial recall of short lists improves for lists that are frequently repeated across trials (e.g., the same list is presented on every third trial). Recent findings investigating variants with partial repetitions of lists support the conclusion that the Hebb effect arises from unitized long-term memory representations of whole lists that are automatically retrieved when at least the initial segment of the current list matches the list represented in long-term memory (Burgess & Hitch, 2006; Hitch, Fastame, & Flude, 2005). The most direct evidence for the acquisition of unitized list representations in the Hebb paradigm comes from a recent study of

Szmalec, Duyck, Vandierendonck, Mata, and Page (2009). In the first phase of their experiment participants recalled lists of nine syllables segmented into three groups of three. Across trials, some groups of three syllables were frequently repeated. In the second phase, participants made speeded lexical decisions. When the three-syllable groups frequently used in the first phase were now presented as nonwords, they were rejected more slowly than comparable nonwords that people were not exposed to. This finding shows that people have formed a unified lexical representation of the three-syllable sequences included in the memory lists, similar to representations of words.

There is some evidence that there is a further mechanism of long-term learning besides the chunking of structures, namely the gradual build-up of associations to reflect the covariation of elements such as events in a sequence. For instance, Majerus, van der Linden, Mulder, Meulemans, and Peters (2004) exposed participants to a continuous sequence of syllables to which they merely listened while engaging in a drawing task. The sequence was governed by an artificial grammar that assigned different probabilities to each pairwise transition between syllables. In a later test of immediate serial recall of lists composed of the same syllables, participants did better on lists that matched the artificial grammar (i.e., had only high-probability transitions) than on lists not matching the grammar. This finding cannot be explained by the acquisition of chunks of lists because the stream of syllables presented in the learning phase was not segmented into lists that could be wrapped into a chunk (for a similar finding see Botvinick & Bylsma, 2005).

I assume that the same two forms of learning occur in procedural long-term memory. It is likely that task sets are represented as chunks that can be retrieved as a whole, to be unpacked into individual stimulus-response bindings in the bridge. I am not aware of direct evidence for the unitization of task-set representations in long-term memory, probably because little research has focused on the acquisition of new task sets. One prediction from the assumption of unitized representations is that retrieval of a task set from long-term memory should be independent of its set size, analogous to retrieval of a memory list. Some initial evidence for this prediction comes from the experiments by Hübner et al. (2004), who found that when people switched between one task with few and one task with many stimulus-response mappings, switch costs were smaller when switching to the task set with many mappings. This is at least consistent with the idea that retrieving a task set with many stimulus-response bindings does not take more time than retrieving a less complex task set. At the same time, there is also evidence that people acquire long-term associations between stimuli and responses given to them, and these associations serve to prime the previous response when the same stimulus is encountered again (e.g., Horner & Henson, 2009; Pösse, Waszak, & Hommel, 2006).

Region of Direct Access and Bridge

Whereas there is no capacity limit on the activation of representations in long-term memory and the amount of associative learning, the more central components of working memory, the direct-access region and the bridge, have limited capacity. The capacity limit of declarative working memory is a limit on the number of elements that can be integrated into a new structure. Because the working-memory concept has its origins in memory research, most attempts to measure its capacity rely on immediate-memory procedures. The capacity limit of declarative working memory, however, is not a limit on retention in memory but on what we can attend to simultaneously and thereby integrate. This is apparent from instances where our capacity to integrate information is limited even though all required information is constantly available to perception. For instance, people have severe difficulties comparing verbal and graphical representations of three-way interactions, and largely fail on four-way interactions (Halford, Baker, McCredden, & Bain, 2004). Interactions are difficult to understand because the effects of individual variables cannot be assessed separately, one after the other. Rather, people have to generate an integrated representation of the joint effects of all variables. For instance, a three-way interaction must be represented by a three-dimensional mental space in which each condition occupies a different corner, to which the outcome of that particular variable combination must be bound. The capacity limit of declarative working memory is a limit on the number of such bindings that can be maintained simultaneously. My colleagues and I designed a number of tasks assessing the ability to integrate visually presented information; these tasks are highly correlated with conventional measures of working memory and are excellent predictors of reasoning ability (Oberauer, Süß, Wilhelm, & Wittmann, 2008).

The capacity limit of procedural working memory is most apparent in people's limitations in dual-task assignments such as the PRP paradigm and variants of it (Pashler, 1994). These dual-task studies reveal that under most circumstances people can carry out only one response selection process at a time. Response selection refers to the selection of the response category that is linked to a stimulus category by a task set. A natural explanation for this "central bottleneck" that enforces serial response selection is by the assumption that the bridge can hold only one task set at a time. Thus, the capacity limit of procedural working memory, like the limit of declarative working memory, can be described as a limit on what we can attend to at the same time.

It is not easy to quantify the capacity of working memory for two reasons. One is that it is not clear what the unit of measurement is. For declarative working memory, Cowan (2005) proposed that capacity is limited in terms of the number of chunks, and estimated the "magical number" to be approximately four chunks. There is evidence that the number of chunks plays an important role, but in addition the complexity of the chunks (e.g., the length of words, the number of features or components in visual objects) also matters (for visual chunks see Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007; for verbal chunks see Chen & Cowan, 2005). On the procedural side, the evidence from dual-task studies points to a "magical number" of just one task set that can be held in the bridge at any time, regardless of how many components (i.e., stimulus and response categories) it consists of.

Thus, it looks like the capacity limit of declarative working memory is measured in more fine-grained units (i.e., the number and the complexity of the individual elements that are bound together into a structure in the direct-access region) than the capacity limit of procedural working memory (i.e., the number of structures created from binding together elements). Whether this is a true difference or not is difficult to determine because nobody has tried to quantify the capacity limit of procedural working memory in terms of the number of elements bound into a task set, or to quantify declarative capacity in terms of the number of integrated structures. We know that reaction times increase as the number of stimulus-response mappings in a task set increases (Hick, 1952), but is there a limit to how many stimulus-response bindings as part of one task set can be maintained at the same time in the bridge? Can a prepared reflex be established for task sets with any number of stimulus-response bindings? This is a question that awaits further research. At the same time, it is possible that declarative working memory, too, is limited to a single integrated structure (e.g., a single mental model or a single list). Research on deductive reasoning with mental models has provided evidence that people hold in working memory only one mental model of a verbal description of a spatial array, even when several alternative arrangements are compatible with the description (Oberauer, Weidenfeld, & Hörnig, 2006; Vandierendonck, Dierckx, & De Vooght, 2004). Thus, it is conceivable that both the region of direct access and the bridge have a capacity limit on two levels of granularity, being limited to a single structure with a limited number of elements.

Evidence on how tightly integrated the components of a structure in working memory are can be obtained by looking at the time demands of updating parts or the whole of a structure. The experiments by Kessler and Meiran (2008) provide some evidence that elements in declarative memory can be updated one by one. Participants remembered three digits in three boxes and updated these digits by working through a self-paced series of updating steps. On each step, another set of three digits was displayed across the three boxes, which differed from the preceding set in zero, one, two, or all three digits. Participants had to always remember the last set of digits. The time they took for each step increased monotonically with the number of digits that changed relative to the preceding set. Vandierendonck, Christiaens, and Liefooghe (2008) conducted a similar study on the updating of procedural working memory. They asked people to classify stimuli that were digits composed of smaller digits. Each trial was preceded by a task cue that specified two dimensions of the task set for the upcoming trial. One dimension was whether the large digit or the small digits forming it were to be used, and the other dimension was whether the digit was to be classified as odd vs. even or as large vs. small. From one trial to the next no, one, or both dimensions could change. Latencies increased from zero to one dimension but did not increase further when both dimensions changed, as would be expected if a task set can only be updated as a whole. Together with the results of Kessler and Meiran (2008), this finding hints at a difference between declarative and procedural working memory: Whereas in declarative working memory individual elements can be updated separately, this seems not to be possible in procedural working memory. This conclusion needs to be qualified, however, in light of the third experiment of Kessler and Meiran (2008), in which they again asked people to udpate on each step between zero and all three digits. This time, however, only those digits that had to be replaced in working memory were presented on each step. Now latencies for updating steps increased from zero to one to two new digits but then dropped sharply for steps on which all three digits were new. This pattern shows that the elements in declarative working memory are integrated into a structure, and when some but not all elements in that structure are updated, the remaining elements must be retrieved so that a new structure can be formed. Thus, the contents of both declarative and procedural working memory are integrated into a structure, although there seem to be differences in the ease with which that structure can be decomposed. The elements of declarative structures can be updated individually as long as new elements are integrated with old ones, but the elements of procedural structures can not be updated individually – any change of one element requires updating of the whole structure.

The second factor complicating the measurement of capacity limits is that performance on any task is determined not only by the contents of central working memory but also by activated long-term memory. The contributions of long-term memory to performance on immediate memory tasks has long been recognized (Burgess & Hitch, 2005; Hulme, Roodenrys, Brown, & Mercer, 1995); the Hebb effect discussed above is one of many examples of how representations in long-term memory assist performance on tasks used to gauge the capacity of declarative working memory. The same complication arises for procedural working memory. For instance, there are two phenomena that at first blush seem to contradict the assumption that only one task set can be held in the bridge at any time. One is the observation of task congruency effects in task-switching paradigms. When people alternate between two tasks that map the same set of stimuli to the same set of responses by different rules (e.g., classifying digits as odd vs. even, or as large vs. small, using left vs. right response keys for both tasks), we can distinguish between stimuli that are mapped to the same response by both tasks (called congruent) and stimuli that are mapped to different responses by the two tasks (called incongruent). Congruent stimuli are responded to faster and more accurately (Rogers & Monsell, 1995). This finding suggests that not only the currently relevant task set but also the currently irrelevant task set contributes to the translation of stimulus information to response information. This could mean that the currently irrelevant task set is held in the bridge, acting as a prepared reflex just like the relevant task set (only weaker). Alternatively, task congruency effects could be explained by associations between stimuli and responses in long-term memory that by-pass the bridge. Because in a typical task-switching experiment both tasks are applied to all stimuli many times, there is ample opportunity for stimulus-response associations reflecting the mappings of both task sets to be learned. The available evidence so far supports the explanation in terms of long-term memory associations. Waszak, Wenke, and Brass (2008) showed that a task set that was instructed for a set of stimuli but never actually applied to those stimuli led to an overall increase of reaction times but produced no task congruency effect. This is as expected if the congruency effect requires the gradual build-up of stimulus-response associations through experience with a task to emerge. Meiran and Kessler (2008) showed that when unfamiliar stimulus and response categories were used to define the instructed task sets, congruency effects emerged only slowly over the course of the experiment, as predicted on the assumption that long-term memory representation of the stimulus and response categories first had to be formed before they could be associated with each other.

The second phenomenon suggesting that two task sets could be held in the bridge simultaneously is the backward compatibility effect (Hommel, 1998a). In a dual-task paradigm that requires a response to each of two stimuli presented in close succession, the response to the first stimulus is speeded up if it is compatible with the response required to the second stimulus. For instance, the first task could be to press a left key in response to a red patch and the right key in response to a yellow patch, and the second task could be to say the word “left” in response to the letter H and the word “right” in response to the letter G. When a red patch is followed by an H, the left key is pressed faster than when a red patch is followed by a G. This finding suggests that the task set mapping the letters to the left-right dimension contributes to the selection of the response to the color stimulus. Again, it is possible that both task sets are held in the bridge, but alternatively, the backward compatibility effect can be explained through stimulus-response associations in long-term memory that mediate priming of one response through the second stimulus, bypassing the bridge. The evidence is ambiguous in this case. Ellenbogen and Meiran (2008) have shown that the backward compatibility effect disappears when the number of stimulus-response mappings of the first task is increased from two to six. This is what would be expected if the bridge has sufficient capacity to hold two task sets as long as both involve only two stimulus-response bindings, but when the first task set already requires six such bindings, the second task set is pushed out of the bridge, eliminating the backward compatibility effect. Evidence for the associative-learning explanation comes from experiments by Hommel and Eglau (2002). They asked people to work on the dual-task paradigm for some time and then dropped the second task. If the backward compatibility effect was due to the task set of the second task being held in the bridge, the effect should disappear immediately after the instructions dropped the second task, because people would remove the now irrelevant task set from the bridge. The backward compatibility effect, however, vanished only gradually over the next 100 trials after the second task was abandoned, as would be expected from a slow, gradual unlearning of stimulus-response associations.

It is conceivable that both associations in long-term memory and bindings implementing the second task set in the bridge contribute to the backward compatibility effect. Other evidence from dual-task studies have provided evidence that under favourable circumstances two tasks can be carried out in parallel with little or no mutual interference (Hazeltine, Ruthruff, & Remington, 2006; Oberauer & Kliegl, 2004), suggesting that the task sets for both tasks are held simultaneously in the bridge. Perhaps the limitation to a single task set is not as hard as it first seemed. One necessary prerequisite for overcoming dual-task costs is practice with the dual-task situation. Another favourable factor is a clear separation of the two task sets so that cross-talk between stimulus representations of one task set and response representations of the other are easily avoided.

A further consideration when comparing capacity limits in declarative and procedural working memory is that the typically used experimental paradigms in the two fields differ in one important aspect: Tasks used to study the capacity of declarative working memory nearly always use novel sets of items to be held in working memory on every trial (for an exception see Oberauer & Risse, 2006). In contrast, tasks used to study the capacity limit of procedural working memory nearly always used the same task sets throughout the experiment (for an exception see Pösse et al., 2006). In other words, experiments on declarative working memory use a varied mapping from cues (such as serial position in a list or the location in a spatial array) to target elements (such as digits, words or shapes), whereas experiments on procedural working memory use a fixed mapping from stimuli to responses. Future research systematically comparing declarative and procedural working memory will have to make sure that the same form of mapping is held constant.

The Focus of Attention

Evidence for a focus of attention in declarative working memory relies on findings indicating that the element last presented (McElree, 2006) or the element last operated upon (Garavan, 1998; Oberauer, 2003) has a privileged status of being faster available for processing than other elements in working memory. This object-repetition benefit might find its counterpart on the procedural side in the response-repetition benefit observed in choice reaction time studies (Bertelson, 1965). If the response focus maintains a representation of the selected response after that response has been executed, then selection of the same representation would be facilitated in the next trial.

More recent investigations into response repetition effects, however, revealed a more complicated picture. Response repetitions are faster and less error prone than response changes only as long as the task remains the same across two successive responses. If the task switches from the first to the second response, response repetition benefits turn into response repetition costs (Druey & Hübner, 2008; Hommel, 1998b; Rogers & Monsell, 1995).

Hommel (1998b) interpreted this interaction by assuming that stimulus and response features of each trial are bound together into *event files*. If a response is repeated across trials while one or several stimulus features change, the bindings of the event file carried over from the preceding trial must be broken up, thereby adding difficulty to a trial with a repeated response. In this interpretation, neither the stimulus representation nor the response representation carries over from one trial to the next – what remains is merely the binding or association between all stimulus and response features that co-occurred on a trial. It is tempting at this point to think of a simplification of the structure of working memory, assuming a single focus of attention that holds unified event files that integrate declarative and procedural representations. Such a move would be premature. It predicts that it should be impossible to maintain an object (such as a letter or a digit) in the focus of attention while the cognitive operation applied to that object (e.g., an addition or subtraction) is changed, or while the response to it changes. Object-repetition benefits, however, are robust across changes of the response computed with the focused object (Oberauer, 2003) and even across switches of the task applied to them (Oberauer & Risse, in press).

An alternative interpretation of the modulation of response-repetition effects by task switching was offered by Druey and Hübner (2008). They surmised that response-repetition benefits arise not from a response representation lingering after execution but rather from a persistent representation of the stimulus category eliciting that response. As long as the task set remains the same, stimulus category and response category are necessarily confounded, and only when the task set is changed, the two can vary independently. If, as Druey and Hübner (2008) argue, the task-switch condition reveals the true status of response representations after their execution, then response-repetition costs could reflect rapid self-inhibition of response representations after their execution. Self-inhibition might serve to avoid perseveration of the response once it has been carried out. If this interpretation is correct, it might hint at a difference of the operating principles of the focus of attention and the response focus: Whereas the content of the response focus is immediately inhibited after being used, the content of the focus of attention lingers on. Before we draw this conclusion, however, it is important to verify that the object-repetition benefit that motivates the notion of representations lingering in the focus of attention cannot be turned into an object-repetition cost by an experimental manipulation analogous to a task switch. Like switching to a new task set turns response-repetition benefits into costs, switching to a new memory set might turn object-repetition benefits into costs. An unpublished experiment from my lab confirmed that prediction (Gade, Druey, & Oberauer, 2010). If object-repetition benefits occur only as long as the memory set from which the object is selected remains the same, we can apply the argument of Druey and Hübner (2008) on response repetition effects also to object repetition effects: As long as the memory set stays the same, repeated access to the same object in that set is confounded with repeated use of the same positional cue (e.g., access to the letter L in the list BFL is always cued by the third position cue). Only when we switch from one memory set (e.g., BFL) to another set (e.g., LNK) can we repeat the object while changing the positional cue (e.g., cue with position 3 in the first set, then cue with position 1 in the second set). If object-repetition benefits are limited to cases where the positional cue is repeated, it is likely that the repetition benefit arises from persistent selection of the cue (e.g., the list position), rather than the object itself (e.g., the letter or digit in that position).

Taken together, the available evidence is compatible with the view that there is a focus of attention in declarative working memory that selects a memory object (e.g., a digit) based on a context cue bound to it (e.g., a list position), and an analogous response focus in procedural working memory that selects a response (e.g., the left key) based a stimulus category bound to it (e.g., a red arrow). Both foci discard of the selected content immediately after its use by inhibiting it, but at the same time maintain the cue, so that a repetition benefit occurs if the cue is repeated but a cost is suffered if the same object or response is selected again based on a different cue.

Shared Capacity?

If declarative and procedural working memory are separate sub-systems, they ought to have separate capacities. This assumption leads to two testable predictions. First, increasing the load on declarative working memory should have relatively little impact on the operation of procedural working memory, and vice versa. Second, individual differences in performance on tasks limited by the capacity of declarative working memory should correlate relatively weakly with performance on tasks limited by the capacity of procedural working memory. "Relatively little" means that the impact of load within one of the sub-systems should be larger than across subsystems, and the correlation of performance measures within a sub-system should correlate more strongly than across sub-systems.

There is, unfortunately, very little evidence speaking to these predictions, and it is far from conclusive. Liefooghe, Vandierendonck, Muyllaert, Verbruggen, and Vanneste (2005) tested the assumption that the phonological loop, a system responsible for maintenance of verbal sequences in Baddeley's (1986) working-memory model, contributes to maintenance of the currently relevant task set. They predicted from this assumption that blocking the phonological loop through articulatory suppression during a task-switching experiment should selectively increase reaction times on no-switch trials. This is because, without articulatory suppression, people have to retrieve a new task set only on switch trials, whereas they can continue using the existing task representation in no-switch trials. With articulatory suppression, the task representation in working memory is damaged and therefore must be retrieved from long-term memory even on no-switch trials. Liefooghe et al. (2005) found evidence in line with their prediction. This finding implies that one activity known to impair declarative working memory (for verbal lists) also impairs procedural working memory (for task sets). Other researchers, however, found that articulatory suppression even increased task switch costs in cued task switching (Miyake, Emerson, Padilla, & Ahn, 2004), and still others found that articulatory suppression slowed switch and no-switch trials to the same degree (Bryck & Mayr, 2005). Bryck and Mayr used regular task sequences and showed that the effect of articulatory suppression arose primarily when participants had to keep track of where they were in the sequence themselves without external task cues. They interpreted their finding as evidence for a separation of two working-memory components, one (which they refer to as the phonological loop) being responsible for maintaining the order of tasks while the other (which they call the global workspace) is fully occupied by the current task set.

Later research reinforces the view that task switching is independent of the concurrent load on declarative working memory. Liefooghe, Barrouillet, Vandierendonck, and Camos (2008) embedded a task-switching paradigm as the processing component into a complex span procedure. In their experiment, participants alternated between encoding a consonant for later recall and carrying out a series of choice tasks at a fixed, computer controlled pace. The series of choice tasks either used only one task set (pure lists) or required alternation between two task sets (mixed lists). Task switch costs were unaffected by the size of the concurrent declarative memory load (i.e., the length of the memory list). Task switching impaired memory for the consonants more than task repetition, but it did so merely by increasing the time required for each response, thereby reducing the time between trials available for refreshing memory traces. The same effect was obtained by slowing down responses through visually degraded stimuli. Thus, there is nothing specific to task switching that interferes with declarative working memory. At the same time, increasing the load on declarative working memory does not affect task switching. This latter conclusion was confirmed by experiments from my own lab (Oberauer & Risse, in press). We asked participants to remember two or four digits, each displayed in a different frame on the screen, and to carry out a self-paced series of arithmetic operations. The size of each operation was indicated by a number displayed in one of the frames, and the kind of operation was cued by the color of that frame. The selected frame indicated which digit the operation had to be applied to; this could be either the same frame as for the preceding operation (object repetition) or a different one. We found that the time cost for object switching were increased as the memory load increased from two to four digits, but the time cost for task switching was not.

These findings are difficult to reconcile with the assumption that maintenance of a set of letters or digits and maintenance of a task set share the same limited capacity. If, contrary to my assumption above, all task sets involved in a block of trials are held in working memory simultaneously, then a complex span with task switching during the processing component should incur a larger overall load (*n* letters + 2 task sets) than a complex span using a single processing task (*n* letters + 1 task set). As a consequence, Liefooghe et al. (2004) should have found larger switch costs with increasing memory load, and an impairment of memory for letters from the addition of a second task set, over and above the impairment due to longer response durations. Under the alternative assumption that working memory can hold only one task set at a time it would be difficult to understand how it can hold one task set plus a list of four digits or up to six letters at the same time without a complete breakdown of performance. There is a third alternative, however, which is to assume that working memory capacity is large enough to accommodate more than one task set, but the system is strongly constrained to hold only one task set at a time – even in dual-task settings where carrying out two tasks simultaneously would be advantageous – for reasons that have nothing to do with the capacity limit of working memory. This version of the shared-capacity hypothesis could be tested by varying the complexity of a single task set employed concurrently with a declarative memory load. I am not aware of any such study.

The existing correlational evidence points more towards common capacity limits of declarative and procedural working memory. Performance in established tests of working memory (e.g., reading span) reflect primarily the capacity of the declarative sub-system, assessed through the number of elements that can be retained and operated upon. Individual differences in the procedural sub-system are not easily assessed in an analogous way, through counting the number of elements of procedural representation. They are best measured through the efficiency with which simple cognitive operations are carried out, which should reflect the strength of the task sets controlling these operations. For instance, the speed and accuracy on choice response tasks with arbitrary stimulus-response mappings should reflect the strength of stimulus-response bindings in the bridge. One study looking at the correlates of four-choice tasks with compatible and arbitrary mappings found that a latent factor reflecting the specific variance in tasks with arbitrary mappings (not shared with analogous tasks with compatible mappings) was highly correlated with a factor for tests of (declarative) working-memory capacity (Wilhelm & Oberauer, 2006). A more refined measure of the strength of stimulus-response bindings in two-choice tasks can be obtained by applying the diffusion model (Ratcliff, 1978), which enables isolating the drift rate as a reflection of the efficiency of response selection from other variables affecting response times. Schmiedek, Oberauer, Wilhelm, Süss, and Wittmann (2007) measured drift rate in eight choice tasks using the EZ diffusion model (Wagenmakers, van der Maas, & Grasman, 2007) and found that specifically the drift rate parameter was strongly correlated with measures of (declarative) working-memory capacity.

Taken together, the present data are best explained by the assumption that declarative and procedural working memory have separate capacities, so that their contents don't interfere with each other, but these capacities are limited by a common factor that varies across individuals, so that they are highly correlated.

Executive Functions

The concept of working memory has often been set in close relation to that of executive functions. As mentioned in the introduction, the concept of executive functions is particularly ill defined (even for the standards of psychology with its track record for vague concepts), and as a consequence, the relation between working memory and executive functions is diffuse. I believe that the present framework can accommodate the notion of executive functions in a well-defined way, thereby helping to clarify this term.

I propose to define *executive functions* as the collection of cognitive functions or processes that serve to control the primary processes directed at solving a task. This definition implies a distinction between primary processes and executive processes. Not every cognitive process guided by task sets in working memory, and using information from declarative representations in working memory is an executive process. It is conceivable that working memory operates without any executive processes – and indeed, when a prepared reflex is carried out, this is what happens: A perceived stimulus or a declarative representation in the focus of attention simply triggers the response specified in the task set currently held in the bridge. Executive processes are involved only at an earlier point, in constructing the task set or in choosing one to be retrieved from long-term memory. Thus, my conceptualization of executive functions differs in one respect from that of Vandierendonck and colleagues (Szmalec et al., 2005; Vandierendonck, Deschuyteneer et al., 2008) because I regard *response selection* as a basic process, not an executive process.

Because the current contents of working memory determine the course of thought and action, executive processes control ongoing cognitive operations through controlling the contents of declarative and of procedural working memory. This involves three kinds of processes: (1) establishing new structures in working memory, such as encoding a new list or setting up a new task set; (2) removing no longer relevant contents from working memory, such as a memory list after it has been declared irrelevant (Oberauer, 2001) or a task set after a task switch has been indicated, and (3) actively maintaining representations in working memory when they are at risk of being lost. The risk of being forgotten arises from interference from competing representations (the contribution of purely time-based decay to forgetting from working memory is minimal at best, see Lewandowsky, Oberauer, & Brown, 2009), so the third kind of process comes down to protecting the current contents of working memory from interference from other representations, either from perception or from long-term memory.

These three kinds of executive processes collaborate to meet three kinds of demands on control of the contents of working memory, summarized in Table 2. The first and most basic kind of demand involves merely setting up and maintaining a new structure in working memory. This could be a list or words or a constellation of objects in declarative working memory, briefly retained for recall or recognition, as in typical short-term memory tasks, or for making inferences from it, as in typical reasoning and text comprehension tasks. On the procedural side, this kind of demand is exemplified by establishing a new task set and executing it, as would be required for carrying out a speeded choice task. Meeting these demands requires a mechanism for quickly establishing strong bindings between representations, for instance to bind memory items to list positions or to bind stimulus categories to response categories.

The second level of demand adds to the first the need to protect the current contents of working memory from interference. Interference can come from perceptual input that attracts attention and thereby is likely to enter working memory, or from contents of long-term memory that become strongly activated and thereby acquire a high chance of entering working memory. An example of interference from long-term memory is given by experimental paradigms of proactive interference (Monsell, 1978; Szmalec, verbruggen, Vandierendonck, & Kemps, in press; Tehan & Humphreys, 1995), demonstrating the intrusion of recent but no longer relevant contents of declarative working memory on current processes. Interference in procedural working memory is frequently studied with paradigms such as the Stroop task and the antisaccade task, in which an arbitrary task set held in the bridge (e.g., say "red" in response to the word "green" printed in red) must be protected against a strong habitual task set in long-term memory (i.e,. say "green" in response to the word "green").

In situations with strong interference researchers often assume that inhibition of the intruding representation is the executive function called for. I suspect that the appeal to inhibition as a magic solution to interference problems is only a place holder for an explanation. Inhibition can resolve interference only on the basis of a representation that clearly distinguishes what is relevant (and therefore needs to be strengthened) and what is irrelevant (and therefore needs to be inhibited). For instance, reading the color word in a Stroop task can be inhibited only on the basis of a representation that binds the two competing tasks, word reading and color naming, to different contexts or "tags" that mark one as the task to be executed and the other as the one to be inhibited. Likewise, a recent but no longer relevant memory list can be inhibited to prevent proactive interference only if the previous, irrelevant list is clearly distinguished from the current, relevant list by binding them to different contexts (Delaney & Sahakyan, 2007). If this reasoning is correct, meeting the second demand on working memory, protection from interference through inhibition, relies again on bindings, but on a higher level than the first level of demand: Here, whole task sets and whole memory sets are bound to contexts that distinguish relevant from irrelevant sets.

The third level of demand on executive processes involves updating of the contents of working memory. This implies partially or completely removing the current contents from the direct-access region or the bridge, and replacing them with new ones. On the declarative side, updating has been studied with a number of paradigms like the “memory updating” task (Ecker, Lewandowsky, Oberauer, & Chee, 2010; Oberauer & Vockenberg, 2009), in which participants update a list of digits or letters through arithmetic operations, or the “keeping track task” (Yntema & Mueser, 1962) in which participants see a long list of nouns from different categories and must remember the last noun of each category. Updating of procedural working memory means to update the current task set, a process intensely investigated in recent years with the task-switching paradigm (for review see Monsell, 2003). Updating has in common with protection from interference that two memory sets or task sets compete for access to the central components of working memory. In the case of resistance to interference, the competition is usually an asymmetric one between an established but irrelevant structure in long-term memory and a relevant ad-hoc structure to be maintained in central working memory. In the case of updating, competition is usually symmetric between two structures that are both created ad hoc, such as a random list of nouns or a task set with arbitrary stimulus-response mappings, and they compete because of a change in which of them is relevant. This difference implies that different basic mechanisms are needed to accomplish these two demands. Fending off interference requires establishing strong bindings between the elements of the relevant set (to establish it as a structure in the direct-access region or the bridge, respectively) and strong bindings of that set to a context that distinguishes it from the competing irrelevant set. Updating, in contrast, requires striking a balance between establishing strong bindings and rapidly dissolving such bindings. For instance, in an antisaccade task efficient performance is best served by a strong binding between “stimulus on the left” and “look right”, and vice versa. In a task-switching paradigm, however, that asks participants to switch on every second trial between the antisaccade task and the prosaccade task, setting up the stimulus-response bindings of each task as strongly as possible is not the best solution. Rather, these bindings must be established strong enough to prevent interference from the competing task but loosely enough to be quickly dismantled and replaced.

The taxonomy of demands on executive processes in working memory proposed in Table 2 matches well onto the available evidence from individual-differences studies on different kinds of executive functions. Miyake and colleagues (2000) analyzed the structure of individual differences in executive functions and distinguished three factors, called *inhibition*, *updating*, and *shifting*. The first factor refers to inhibition of strong but wrong action tendencies in tasks such as the Stroop or the antisaccade paradigm, and it corresponds to the protection from interference in procedural working memory in my taxonomy. Updating refers to updating the contents of declarative working memory, measured by tasks such as the keep-track task (Yntema & Mueser, 1962). Shifting refers to the task switching paradigm, which in my taxonomy represents updating of procedural working memory. A follow-up study by Friedman and Miyake (2004) distinguishes two factors of inhibition, one reflecting inhibition of pre-potent responses in speeded response tasks, and the other reflecting the prevention of proactive interference in episodic memory tasks. These two factors map onto the prevention of interference in procedural and in declarative memory, respectively.

The present taxonomy summarized in Table 2 (Oberauer, 2009) is an attempt to provide a systematic framework for the collection of executive functions that so far have accrued in the literature as a seemingly arbitrary list. At the same time, I tried to make explicit the relation between working memory and executive functions: Executive processes control our thoughts and actions through controlling the content of working memory.

Concluding Remarks

My concluding remarks will be brief because I have nothing conclusive to say. I proposed a highly speculative framework for integrating two lines of research on capacity limits of cognition, work on immediate memory on the one hand, and work on response selection and action control on the other hand. My speculations were motivated by the belief that the concept of “working memory” contains a promise that has not yet been fulfilled, to aim at an integrated understanding of how the cognitive system maintains information available and how it works on and with that information. I have proposed that the “working” side and the “memory” side have parallel structures and analogous processing principles mainly because I think that this analogy is a fruitful heuristic for generating new hypotheses. I am confident that, as research progresses, this analogy will eventually fail, but I hope it will fail in interesting ways.

Table 1

Corresponding components of declarative and procedural working memory

Declarative WM	Procedural WM
Activated declarative WM Maintains sets of memory items not immediately relevant in a state where they are easy to retrieve *- Activated chunks of sets (unpacked at retrieval); retrieval time independent of set size (Oberauer, 2005)* *- Associations reflecting transition probabilities (Majerus et al., 2005)*	**Activated procedural WM** Maintains task sets not relevant for the upcoming cognitive operation in a state where they are easy to retrieve (e.g., for a rapid task switch) *- Activated unified representations of task sets (unpacked at retrieval); retrieval time independent of number of S-R mappings (Hübner et al., 2004)* *- Associations of stimuli and responses: priming of responses bypassing the bridge (backward compatibility effect, task congruency effect)*
Region of Direct Access Maintains set of items that must be accessed for current cognitive operations; binds items to their positions in that set *- Capacity limit on the number of elements in a new structure* *- Limitation to a single structure?* *- Set-size effect on RTs of currently relevant (to be accessed) list; (Oberauer, 2005);*	**Bridge** Maintains the task set for the upcoming cognitive operation; binds stimulus categories to response categories in that set *- Capacity limit on the number of S-R bindings in a task set?* *- Limitation to a single task set* *- Set-size effect of currently relevant task set (Hick, 1952);*
Focus of attention for objects Holds one item ("object") selected for processing. *- Object switch costs (Oberauer, 2003)* *- Object-repetition costs when list is switched (Gade et al., 2010)*	**Response focus** Maintains one response selected for execution *- Response switching costs (Bertelson, 1965)* *- Response-repetition costs when task set is switched (Rogers & Monsell, 1995)*

Table 2

Demands on Working Memory and Executive Processes

Demand	Declarative WM	Procedural WM
Establishing new content (“Storage” / “Processing”)	Immediate recall or recognition of lists or spatial arrays *Digit span, Corsi block*	Establishing and executing a task set *Choice response task, mental arithmetic*
Protecting content from interference (“Inhibition”)	Overcoming interference from declarative LTM; preventing interference from distractor stimuli *Proactive-interference paradigms, recent-probes task*	Overcoming interference from procedural LTM (“prepotent responses”) and irrelevant instructions *Stroop task, antisaccade task*
Removing old content, establishing new content (“Updating”)	Replacing current memory sets or elements with new ones *Memory updating task, keep-track task*	Replacing current task set with new one *Task-set switching*

Note: Examples are given in italics. Explanations of tasks not commonly known: Corsi block = recalling a set of spatial positions in order; recent-probes task = short-term recognition task where the test probe matches not the current list but the list from a recent trial; memory updating task = updating digits held in memory by the result of arithmetic operations applied to them, or updating positions of dots in a matrix by mental shifts; keep-track = watching a long list of nouns from *n* different categories, remembering the last noun in each category.

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