



Review

Basic operations in working memory: Contributions from functional imaging studies

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ABSTRACT

Working memory (WM) constitutes a fundamental aspect of human cognition. It refers to the ability to keep information active for further use, while allowing it to be prioritized, modified and protected from interference. Much research has addressed the storage function of WM, however, its ‘working’ aspect still remains underspecified. Many operations that work on the contents of WM do not appear specific to WM. The present review focuses on those operations that we consider “basic” because they operate in the service of memory itself, by providing its basic functionality of retaining information active, in a stable yet flexible way. Based on current process models of WM we review five strands of research: (1) mnemonic selection of one item amongst others, (2) updating the focus of attention with the selected item, (3) updating the content of visual WM with new item(s), (4) rehearsal of visuospatial information and (5) coping with interference. We discuss the neuronal substrates underlying those operations obtained with functional magnetic resonance imaging and relate them to findings on “executive functions”. The presented data support the view that WM emerges from interactions between higher sensory, attentional and mnemonic functions, with separable neural bases. However, interference processing and the representation of rule switching in WM may demand an extension of the current WM models by executive control functions.

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1. Introduction

Higher-order cognition such as reasoning and problem solving usually requires multiple pieces of information to be related orderly to reach an optimal solution or a correct conclusion. Herein cognition strongly relies on the ability to retain some information active for further use, and to do so in a flexible way allowing information to be prioritized, added or removed. This capability has been named

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“working memory”, and ever since its introduction by Miller et al. [1], cognitive and clinical neuroscientists have attempted to elucidate its components, associated processes and their underlying neural substrates.

In the neurosciences, much of the research on working memory (WM) has concentrated on one of its most pertinent qualities: to retain information over some period of time, when the physical stimulus is no longer present. To accomplish this, the contents of WM are vastly reduced compared to the wealth of information continuously streamed by our senses. The most commonly noted capacity constraint lies at about 4 items [2]. Also, information about some perceptual details may be lost in the mnemonic stimulus representation. Despite these obvious differences between perception and memory, many processes that operate on sensory stimuli may operate equivalently on WM contents. For example, judging which of two simultaneously presented visual stimuli has a higher contrast can similarly be performed on mental representations. Likewise, attention can be shifted between sensory stimuli or between memory items, and both processes involve largely overlapping brain regions [3,4].

This notion is in accordance with the contemporary view that WM is not a self-contained system that is composed of a specific set of brain regions separate from those subserving perception [5–9]. Instead WM is seen as emergent from the interaction of higher sensory, attentional and mnemonic component processes involving their underlying brain regions. For example, higher visual areas subserving the perception of faces and places are also involved in retaining information on faces/places in WM [10]. Activity in perceptual areas is thought to be sustained (or re-activated) by ongoing top-down signals, i.e. attention, from prefrontal and parietal cortex, allowing us to maintain stimulus information in WM for some seconds. In consequence of this concurrence of their structural neuroanatomical bases, perception and memory may also share many operations. Thus, many operations performed on the contents of WM are most likely not uniquely and specifically dedicated to WM. As a consequence, simply listing potential operations on the contents of WM is not appropriate for identifying the basic operations that compose WM (and reviewing the evidence for these). Rather we seek to review those basic operations that make WM emerge – even if they may be “borrowed” from e.g. attentional and general mnemonic systems.

We consider those operations as “basic” that in the context of memory tasks operate in service of memory itself, to provide its basic functionality of retaining information active, in a stable yet flexible way. We focus on operations that go beyond the mere passive maintenance of stimuli, and also leave aside the principles of encoding items into WM. In short, the focus of the present review is on those processes that make WM work, not on all possible operations that can be applied to the contents of WM. This distinction is essential; however, these categories may not be mutually exclusive. We try to define each of the selected operations in the theoretical context provided by Cowan and Oberauer’s process model of WM [11,12] which will be described in some detail below. This will be followed by summaries and discussions of studies on the following operations in WM that we consider as “basic” for its functioning.

(1) Selection: in most circumstances (but only few experiments), not all the representations held in memory are of equal importance all the time, thus requiring some sort of selection or prioritization according to their momentary relevance. For example at an airport, you may have to remember different pieces of information like the terminal number, flight number, gate number and your seat. Their momentary relevance depends on which steps you have already taken. You will not need your seat number before boarding the plane, but by then the terminal number has long become unimportant. The mental selection of one item amongst others as a means of

prioritizing items is the first basic operation we review. (2) Focus updating: recently, on the foundation of Cowan’s and Oberauer’s model [11,12], we have demonstrated that mnemonic selection and attentional focusing, which naturally co-occur and in consequence had not been studied separately in the studies reviewed in the “selection” section, have dissociable neural substrates. (3) Content updating: returning to the example, arriving at the check-in you may find that your ticket has been re-scheduled to another flight due to overbooking. You therefore have to discard the formerly relevant information and replace it with the newly learned data. In the literature this type of requirement mostly is termed “updating” of memory contents. (4) Rehearsal: in order not to have to look up the flight info repeatedly you may silently rehearse it to prevent forgetting. (5) Coping with interference: when re-scheduled, or just by being confronted with announcements for other flights, your WM contents are easily overwritten or confused with one another. Coping with potentially interfering signals is another basic function that is of vast importance in real-life settings. While selection, updating of the focus of attention and updating the contents of WM provide means for the flexibility of WM, rehearsal and mechanisms of coping with interference are main sources of maintaining items stable in WM.

Following these sections, we summarize and discuss these operations and their potential neural substrates. They are related to “executive functions” and cognitive control.

1.1. Cognitive models of working memory

According to the seminal “multiple-component model” by Baddeley and Hitch [13], WM has been conceptualized as a system made up of two specialized temporary memory buffers (a phonological and a visuospatial store), and a supervisory system (the central executive). While the storage systems hold and refresh memory traces in their dedicated content domain for a few seconds, the central executive is involved in control and regulation of WM. Even though the authors did not explicitly assign its components to structural anatomical regions [14], much of the neuroscientific research stimulated by this model did interpret its components literally and sought for dedicated brain regions. In contrast to Baddeley and Hitch [13], Cowan [11] explicitly considers WM not as a separate system but as a functional state that allows a direct access to information. Specifically, his “embedded-processes model” combines hierarchically arranged faculties comprising long-term memory (LTM), the subset of LTM that is currently activated and the subset of activated memory that is in the focus of attention. The activated memory reflects representations of incoming stimuli and previous cognitive operations. The portion of activated memory that is not in the focus of attention is regarded as passive and hence is prone to decay and interference. In contrast, the items in the focus of attention are maintained actively, but their number is tightly limited. The focus of attention may hold up to four of the activated representations. As commonly assumed for attention, the focus can be driven by exogenous stimuli or be voluntarily controlled and directed.

Oberauer [12] extended Cowan’s model [11] by adding a further component, a more narrow focus of attention that holds only one representation at a time (Fig. 1). The one-element focus and the four-element focus refer to two different functional states of accessibility for cognitive processes. Whereas the four-element focus holds a limited number of representations available for use in ongoing cognitive processes, the one-element attentional focus hosts the single representation that is actually selected as the object of the next cognitive operation. Thus, Oberauer [12] argued that the role of the focus is not to hold a set of memory elements ready for access but to hold a single object already selected for processing.

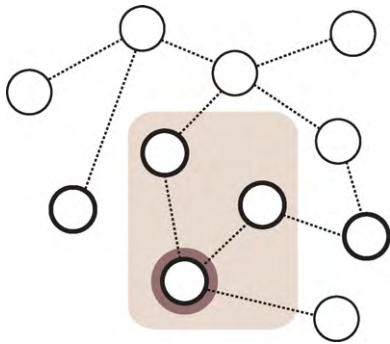


Fig. 1. Oberauer's model of working memory (adapted from [12]). Nodes and lines represent a network of long-term memory representations, some of which are activated (black nodes). A subset of these items is held in a region of direct access (gray field). Within the region of direct access, one item is selected for processing by the focus of attention (dark gray circle).

2. Neuroimaging studies of working memory operations

2.1. Selection of an item representation

Most cognitive tasks require simultaneously holding a number of item representations. In the course of task processing some items in WM become transiently more important than others. Hence, speaking in terms of the Cowan [11] and Oberauer [12] model, while all items are to be retained active, one of them has to be selected and pushed in the focus of attention, hereby achieving higher priority and becoming accessible to further cognitive operations. In this section we review studies that have examined these processes.

In a series of fMRI studies, Rowe and Passingham [15,16] investigated which brain regions were involved in the process of selecting an item in mind. In their studies, selection has been operationally defined as the mental capacity to choose one out of three spatial positions held in WM on the basis of an indirect cue. Specifically, participants maintained three dot positions over a delay phase of varying length (9.5–18.5 s), after which a cue line indicated which position should be retrieved to guide a response (moving a cursor to the selected position using a joystick) [15]. In control trials, the visual and motor components of the task were similar but the participants were not required to remember spatial locations or select a position in memory, but the position was indicated directly. In a second study [16] participants were asked to maintain both spatial locations and their temporal order. A number cue denoted whether the first, second or third position had to be selected for response. Control trials now required to remember the spatial and serial positions but did not demand mnemonic selection. Brain activations associated with the selection of an item in WM were observed in prefrontal (dorsolateral, orbitofrontal and ventral) and parietal (medial parietal and intraparietal) cortex. In contrast, the maintenance of the positions (contrasted with equivalent non-memory periods in control trials in the first study, with baseline in the second study) was associated with bilateral activation of superior prefrontal and intraparietal cortex. Based on these results Rowe et al. concluded that in particular the activity of the prefrontal cortex (PFC) is closely tied to the process of selection and does not reflect memory storage as such.

Johnson et al. [17–19] studied the neural correlates of bringing a memory to one's mind with a different approach: they defined a refreshing operation as an act of thinking back to a single just-seen stimulus, by which this item is "foregrounded", or – in model terms – is selected and moved in the focus of attention. Most of the studies by Johnson and colleagues used verbal materials but some of them also included visual stimuli. For example, in a study by Johnson et al. [17] participants read a word or viewed a visual

stimulus (line drawing of an object or abstract pattern). After a short delay (550 ms) subjects were cued to think back to the just-presented item. Similar to Rowe et al. [15,16], greater activity in the left PFC was associated with the refreshing operation as compared to a control condition in which subjects viewed a new item or the same item again. In addition, some differences in the distribution of activity across left PFC were observed depending on the type of material being refreshed. These results were confirmed by a meta analysis [18] that identified similar regions in left PFC (dorsolateral, anterior, and ventrolateral) associated to varying degrees with refreshing different types of information (visual and auditory words, drawings, patterns, people, places, or locations). The studies by Johnson et al. [17,18] focused on the role of the PFC; however, refreshing-related activities were also present in the parietal lobes (see for example Fig. 2 in [17]). In a more recent study using a slightly modified paradigm [19] participants saw slides including faces and scenes and, after a short delay, either viewed another image or saw a cue that instructed them to perform a refresh of the just-seen picture (face or house). Again, refresh-related activity in PFC was observed. Interestingly, refreshing faces and scenes also modulated activity in the fusiform face area and the parahippocampal place area, respectively. These regions are known to be selectively involved in face versus scene perception. Refreshing thus may lead to a re-initiation of activation in the respective feature-coding region of extrastriate cortex that may be similar to attentively encoding a stimulus into WM.

The studies by Rowe et al. and Johnson et al. [15–19] have emphasized the aspect of actively accessing an item representation. However, these studies also included the act of focusing attention on this item. A series of studies conducted by Nobre and coworkers [20,21] addressed the orienting of attention to perceptual as opposed to memory items. Specifically, Nobre et al. [21] examined whether the same neural system that is involved in shifting attention between locations in the external world also subserves shifting spatial attention between locations stored in WM. They presented spatial cues before (precues) or after (retrocues) the sample array embedded in a visual delayed-match-to-sample task. While the precue enabled participants to shift attention toward the relevant location in the upcoming sample array, the retrocue required participants to shift attention toward the relevant location in the array held as a mental representation in WM. Both cues predicted the likely location of the probe stimulus and led to significant benefits in accuracy and reaction time compared to uninformative cues. Brain areas supporting spatial shifts of attention to external or internal events were identified by comparing activations in response to precues and retrocues with those elicited by neutral cues. Nobre and colleagues [21] found common activations bilaterally in the posterior parietal cortex (including precuneus [PCN], superior parietal lobule, intraparietal sulcus) and frontal cortex (including caudal superior frontal sulcus [cSFS]) that overlapped between pre- and retro-cues. The same fronto-parietal regions have frequently been observed in typical spatial attention paradigms that do not impose strong memory demands [22–24]. In addition, retro-cueing led to selective signal increases in the dorsolateral prefrontal cortex (dlPFC), a region also described by Rowe and Johnson [15–19]. In a follow-up study Lepsien et al. [25] additionally varied the number of items in the sample array in order to separate the contributions of retro-cueing versus simple memory storage. Again, the aforementioned frontal and parietal regions well-known from attentional tasks were activated during orienting the focus of attention to an internal representation.

These results are consistent with a study by Leung et al. [26] who used a parametric manipulation of directing attention to spatial positions within WM. They confronted participants with a variable number of cue arrows (0, 3, 6, 9, and 12) during the delay phase indicating to which of the four neighboring cells within a 4 by 4

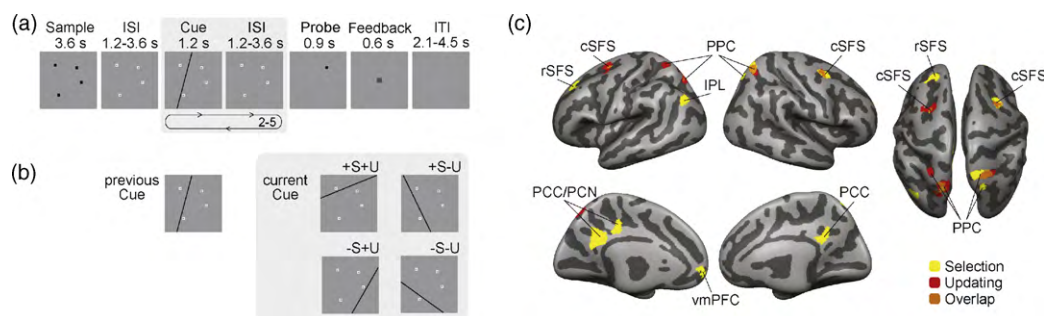


Fig. 2. (a) Paradigm by Bledowski et al. [27] for an independent manipulation of selection and focus updating. Subjects saw four dots (black) and retained their locations in working memory (indicated here by white squares for illustration only). After a variable interval, a cue line ran through the vicinity of one or two of the dots. Participants were asked to select in their mind the location of the dot that was closest to the cue line and maintain it as a specific target item. The number of cue presentations varied from two up to five. At the end of a trial subjects judged whether a probe matched the dot position that had been cued by the immediately preceding line and received a feedback. (b) The sequence of cues determined the demands for updating: during the high-selection/update condition (+S+U), the cue line ran through the vicinity of two of the encoded dots requiring the selection of the closer dot position. In addition, the cue indicated a different target dot as on the immediately preceding cue presentation, thus needing an update of the focus of attention. In the high selection/no-update condition (+S–U), the cue was ambiguous too, but indicated the same target as the preceding cue, hence not requiring a change of the focus of attention. In the low-selection/update condition (–S+U), the cue line ran through the vicinity of only one dot and required an update of the focus of attention. In the low-selection/no-update condition (–S–U), a cue unambiguously denoted the same target as in the preceding presentation. (c) Distinct set of activations sensitive to the manipulation of selection (yellow) and focus updating (red) projected onto the surface cortex reconstruction of the SPM canonical single-subject brain. Areas of overlap are shown in orange. For details see Figure 3 and Table 1 in Bledowski et al. [27].

grid a target position should be mentally moved. With increasing number of attentional shifts activity increased monotonically, in particular in the superior frontal and posterior parietal cortex, i.e. in the very same set of frontal and parietal regions as observed by Nobre and colleagues [20,21].

In summary, studies on the selection of an item representation in memory have yielded activations in diverse brain regions, such as medial and lateral prefrontal and parietal cortex. On the model level, these are likely to represent a mixture of activations due to the selection of an item representation per se and the ensuing attentional focusing of this item. A differential weighting of these two operations across the referenced studies may explain some seemingly contradictory results. Nobre et al. [21] concluded that perceptual and mnemonic shifting of attention is subserved by common regions in parietal and superior frontal cortex. In contrast, Rowe et al. [15,16] had termed their process under examination “attentional selection”, and found that prefrontal cortex, but neither superior frontal nor parietal cortex played a significant role in the selection process. However, in the studies by Nobre et al. [21], the analyses aimed at elaborating the commonalities between perceptual and mnemonic shifting, in consequence their results may be based more on attentional focusing than on memory selection (that had not been demanded in the perceptual condition). In contrast, in the pioneering study by Rowe and Passingham [16], both the memory and the perceptual control condition demanded a shift of attention to the target position, but memory selection had only been necessary in the experimental condition, in which they found increased dlPFC activation.

Thus, most likely a mixture of two different processes was studied by Nobre and Rowe [15,21] using similar labels, leading to apparently discrepant results. These may be reconciled by assuming that mnemonic selection and attentional updating had been involved in varying proportions across studies. We sought to gather evidence on these two processes and identify their substrates by varying them independently in a single study which will be described in the next section.

2.2. Separation of selection and updating

As in the studies described in the previous section, selection and updating mostly work hand in hand: the relevant item is retrieved and the focus of attention is directed to this retrieved item. We recently investigated whether despite their high rate

of co-occurrence these hypothetically different operations have separable neural substrates [27]. In our spatial WM paradigm participants held four locations in WM while they were confronted with a series of cues, the position and sequence of which were designed to impose variable demands for selection among alternative candidate items, independent of the requirement to update the focus of attention. These cues consisted of lines running through the vicinity of one or two of the memorized positions (Fig. 2). Participants were asked to focus in mind the memorized position closest to the line in order to be able to perform rapidly a subsequent and unpredictable match-to-sample test. Each of the series of line cues determined a low or high need for selection depending on whether it was close to only one or to two of the remembered positions, thus requiring the retrieval of a single versus two items. With respect to updating, the very same position could be cued by two successive cues. Here the focus would not be updated but remain on the same item. Alternatively a different position could be indicated, thus demanding an update of the attentional focus.

We found that selection and updating are subserved by distinct brain regions supporting the hypothesis that they may represent distinct WM operations (Fig. 2c). In particular, the set of brain areas exclusively sensitive to the manipulation of selection comprised left rostral superior frontal sulcus (rSFS) and posterior cingulate cortex/precuneus (PCC/PCN). In contrast, whenever an update of the focus of attention was needed we observed activation of the bilateral cSFS and posterior parietal cortex (PPC), regardless of the selection demands. No brain area exhibited a significant interaction between effects of selection and updating.

Thus, reconciling the previously heterogeneous results we could show that, in keeping with Nobre, Leung and colleagues [21,26], cSFS and PPC are implicated in focusing attention on a memory representation. The selection operation that retrieves the most relevant memory item, on the other hand, was subserved by a distinct set of fronto-parietal areas, rSFS and PCC/PCN. Even though selection-related activity in PCC/PCN was reported by Rowe and Passingham [15], our results were in contrast to Rowe’s and Johnson’s [15–19] interpretation who had assigned dlPFC a key role in the selection of a memory representation. In our study, dlPFC was activated above baseline in all four selection/updating conditions. This may suggest that the dlPFC activation for selection is present even with relatively low selection demands and does not depend on the number of re-activated or attended items between which one has to select (see paradigm descriptions for Rowe’s and

Johnson's studies above). Thus it may possibly not reflect selection as such, but may be elicited by being prepared for selection already. In contrast, activity of the rSFS and PCC/PCN varied with demands on selection between items in memory. These areas are known for their sensitivity to retrieval processes in episodic memory, in particular when recall of a specific item is required [28]. This corresponds well to both Oberauer's model [12] and behavioral data indicating that the access to representations stored in LTM is mediated by the same cue-based mechanism that retrieves representations that are outside of the focus of attention [29,30].

Moreover, there is also a high degree of overlap between our selection-sensitive regions and the activation foci from studies on perceptual decision making [31,32]. We acknowledge that because our task also involved a decision of which of the remembered positions is closest to the cue line, we cannot definitely decide whether activation of rSFS and/or PCC/PCN reflects the decision which of the representations is most relevant or the selection as such.

2.3. Updating the memory content

In contrast to the use of the term "updating" of the focus of attention in the preceding paragraph, several studies have investigated the "updating" of the WM contents. While the former definition refers to a change of the attentional focus, making another item accessible to operation while leaving the contents of WM untouched, the latter refers to updating in the sense of a change of the WM contents. In most studies this involved the replacement of a stored, but now irrelevant item with a new input.

Earlier studies have examined updating of WM contents with the n-back task, in which participants are presented a continuous series of items (typically letters) and are asked to indicate whether the given item matches the one from n steps earlier in the sequence. Performance on the n-back task was associated with activity changes broadly distributed over the brain including mainly the prefrontal regions (dlPFC, inferior frontal and anterior cingulate cortex) as well as posterior parietal cortex (for example see review by Collette et al. [33]). However, the results of these studies cannot be interpreted unambiguously because each item presentation not only requires recognition, evaluation and encoding activity but also the replacement (content updating) and reposition (reorganization) of items within WM. Furthermore, subjects also had to inhibit a positive response when an item matched a memory representation but had a different sequential position (e.g. one instead of two steps ago).

In order to overcome these limitations Roth and colleagues [34] have developed a new task in which participants viewed a continuous stream of either faces or houses and indicated whether the current stimulus matched a sample stimulus defined as the first object in the task block. In addition, every 4–10 s, participants were cued with one of two well-memorized faces or houses (learned before the experiment) either to continue to maintain the current target or to replace it with the next picture as the new sought-after target (update of the WM contents). Contrasting the update cue events with the maintenance cue events revealed a transient increase of activity in attention-related regions (cSFS and PPC). Additional activations were observed in several areas including dlPFC, inferior frontal junction, anterior cingulate cortex, inferior occipitotemporal and parahippocampal gyrus.

In consistence with findings described in the previous paragraphs, the results presented by Roth et al. [34] fit to the view that cSFS and PPC subserve a basic operation that directs the focus of attention either towards a memory representation or towards new perceptual input. The activities in the extrastriate and ventrolateral frontal cortex may mediate visual processing and encoding of new information into WM as required when updating the contents of WM.

2.4. Rehearsal

The selection and updating processes described in the previous sections provide flexible use of WM by allowing for prioritization of memory items and updating the stored information. Hereby these operations promote the adaptation to varying task contexts and changes. They may, however, additionally subserve representational stability. For spatial information the hypothesis has been put forward that it is retained by attention-based rehearsal, that is by serial shifts of attention to the to-be-remembered positions [3,6,35,36]. Thus, rehearsal of spatial memoranda could be conceived of as a series of attentional updating events. In accordance with this notion, fMRI recordings have revealed activation in cSFS and PPC during visuospatial rehearsal [37–39].

2.5. Coping with interference

In real-life situations the stability of item representations is threatened by tempting but irrelevant information from various sources: (1) external stimuli may act as distracters and have a detrimental effect on the stable maintenance of items in memory ("distraction"). (2) WM of currently relevant items may be impaired by items that had been relevant previously ("proactive interference"). (3) Items may be confused with one another ("inter-item interference"). We are not aware of any functional imaging study concerning interference amongst memory items, so the following paragraphs will only deal with distraction and proactive interference.

In the model, distraction may operate on multiple levels: First, a WM item may be overwritten by a distracter. Second, an irrelevant item may capture attention in a bottom-up manner and thereby direct attention away from items that should be held active in WM, leaving them prone to decay. Third, an attention-demanding task (in dual task paradigms) interrupts WM processing, both by diverting attention and by disrupting potential efforts of rehearsal.

WM processing in the presence of interfering external stimuli has consistently been found to elicit activation of the dlPFC [40–44]. In an influential study Sakai et al. [43] used a delayed-match-to-sample task which incorporated an additional distracter task within the delay period. In particular, participants memorized a sequence of five red spatial positions. During the delay period the distracter task, a spatial delayed-match-to-sample task, required them to encode, remember and recognize the positions of five blue dots. After completing distracter probe recognition, participants were tested on their memory for the serial order of the red positions from the main task. Sakai et al. [43] showed that dlPFC was selectively involved in protecting WM representations against distraction. More specifically, they found sustained activity in dlPFC in the distracter condition (as compared to control condition without distracting task) during the memory delay on correct trials but not on error trials. They argued that in contrast to "simple maintenance" the dlPFC is involved in "active maintenance", i.e. in protecting memory against interference from distracting and irrelevant stimuli. In that study, interference may have displayed its effects either via capturing attention, hereby leaving WM items prone to decay, or by the interruption of attentional processing in coping with the dual task situation. A recent study by Clapp et al. [40] suggests dissociable bases of interruption of delay-spanning WM processing by multi-tasking as opposed to mere distraction by irrelevant external stimuli. In their study, dlPFC was more strongly activated by multi-tasking than by distraction, and showed a distinct connectivity pattern with visual association cortex between the conditions.

The second type of interference, "proactive interference" (PI), is mostly operationalized by presenting a probe stimulus in a delayed-match-to-sample task, that is not part of the current set

of items held in WM, but was an item of the previous trial (“recent probe”), leading to increased reaction times and error rates when compared to “non-recent probe” trials. In Cowan’s model [11] the previous contents of WM and perception are thought to remain activated portions of memory, that gradually fall back into their inactivated state, as they are not actively attended.

Converging results from a number of neuroimaging studies implicate mid-ventrolateral PFC (vlPFC) and – less consistently – anterior prefrontal cortex and the anterior cingulate cortex in the processing of PI [45–48]. From increased activation on “recent probe” trials alone we cannot tell whether this reflects the activation of the memory trace, conflict resolution, or a response conflict due to the need to respond negatively to a familiar item. Nelson et al. [46] investigated whether this activation is specific for PI in the context of WM by imposing conflict in a WM task and a semantic verb generation task. Activation of vlPFC was found in both, suggesting that it reflects an elemental control process during retrieval from both WM and semantic memory. Strong evidence for a causal role of vlPFC in PI resolution has been provided by a recent study by Feredoes et al. [47]. The authors used TMS to interfere with conflict processing, and found stimulation of the vlPFC but not control sites to disrupt the accuracy for PI trials. Last, Jimura et al. [48] used a modified paradigm to dissociate PI from response requirements. They found that PI led to stronger activation in vlPFC independent of response requirements.

Thus, in contrast to distraction and interruption of WM processing, PI seems to impose a basic, possibly semantic mechanism of interference resolution subserved by vlPFC. However, it should be noted that in contrast to the other studies reviewed here, all studies mentioned above have used verbal instead of visual or spatial stimuli. Postle et al. [49] had implemented seven different materials including verbal, spatial and visual-nonspatial types into a single study, and did not find significant activation of vlPFC. However, the different materials showed vast differences in their capability to raise behavioral effects of PI, and this variability may have eliminated potential effects in vlPFC for some of the non-verbal materials. Similarly, Badre and Wagner [50] did not find reliable vlPFC activation for abstract visual pattern stimuli. However, in their study, matches were not correctly recognized in on average more than 30% of the trials, which strongly limits the conclusions that may be drawn from this result: it is hard to imagine that a stimulus that cannot be correctly remembered invokes a conflict on the following trial. A study by Rahm et al. [51] has found conflict-related activation at a similar location using color stimuli. In that study, stronger vlPFC activation was observed both when a target color was presented as a probe that was flanked by a non-target distracter stimulus or when a non-target probe was flanked by a target color, compared to trials with congruent probe and distracter colors. Conflict resolution in that task may involve a similar mechanism of disambiguation. However, due to the apparent differences in the tasks used and their exact requirements, it remains speculative to assume that processing of PI in the visual or spatial domain will entail activation of vlPFC.

3. Discussion

Much evidence has been accumulated on the storage aspect of WM, however, its ‘working’ aspect is still underspecified. Many operations on perceptual input can also be performed in visual WM, but are not functions of WM as such. Here we sought to isolate those operations that are “basic” for WM functioning, i.e. that keep momentarily relevant information in a stable, yet flexibly accessible state. These operations are not necessarily self-contained but may be “borrowed” from other cognitive functions, in particular attention and memory. Based on Cowan [11] and Oberauer’s [12]

process model of WM we have summarized findings on five strands of research: (1) mnemonic selection of one item amongst others, (2) updating the focus of attention with the selected item, (3) updating the content of visual WM with new item(s), (4) rehearsal of visuospatial information and (5) coping with interference. The first two operations underlie the flexible prioritization of items already held in WM. Updating of WM contents additionally demands the encoding of a new item. Rehearsal and diverse mechanisms of protection against interference underlie the stability of memory traces, especially in the presence of other, (now) irrelevant information. Rehearsal and content updating may largely build upon selection and attentional updating, but comprise additional mechanisms, and were therefore treated in separate paragraphs.

Despite some variability, distinct sets of brain regions are likely to support different basic operations in WM. In particular, the activation of rSFS and PCC/PCN may specifically subserve mnemonic selection of an item in WM [27]. The role of dlPFC for selection has been emphasized in several studies, however, it was insensitive to the manipulation of selection demands [27]. In contrast, updating the focus of attention activates bilateral cSFS and PPC [21,25–27]. Updating the WM content additionally engages extrastriate, ventrolateral and medial frontal cortex which may support encoding of the new input, along with attentional and mnemonic processes [34]. Rehearsal seems to primarily involve the mechanisms of updating the attentional focus. Finally, studies of coping with interference have most consistently reported activation of dlPFC in the presence of distraction [40–44] and of vlPFC during resolving PI from previous trials [45].

Taken together, the presented evidence supports the view that WM emerges from interactions between brain regions supporting higher sensory, attentional and mnemonic systems [3,5–9]. Yet, the results accentuate the independent contributions of the mnemonic and the attentional component functions, and control over interference does not seem to be fully explained in terms of a conception taking into account memory and attention only. Concerning attention, our results [27] are in line with evidence presented by Nobre and colleagues [21] showing that activations of rSFS and PPC were activated by shifts of attention to both visual stimuli and mental representations. Concerning the mnemonic part of WM functioning, we have noted that the same brain regions that subserve mnemonic selection in visual WM are also associated with retrieving information from episodic memory [27,28]. While here we reviewed studies on visual WM only, there is some neuroimaging evidence on verbal WM that is explicitly based on Cowan and Oberauer’s model [11,12], and these studies have yielded comparable results. For example, Nee and Jonides [52] instructed their participants to remember short word lists in a delayed-match-to-sample task, while varying the list position matching the probe. They showed that selection of items outside of the focus of attention more strongly recruited brain regions similar to those implicated in retrieval from LTM than when probing items in the focus of attention. Again, these results highlight the separation of mnemonic and attentional contributions to WM.

3.1. Basic operations in WM and their relation to executive functions

Here we have introduced the term “basic operations” to characterize those functions that help WM provide its basic functionality. This term is not currently used in the literature and the main purpose of introducing it was twofold: (1) to put the focus on the operational – “working” – aspect of WM while at the same time keeping it at a basic level, not implying more complex cognitive functions or the multiplicity of operations that may be performed on the contents of WM. Rather, the term “basic operations” refers to those functions that effectively form the workspace on which

higher cognitive functions may act. (2) We sought to distinguish them from so-called executive functions, in order to keep a relatively narrow focus on WM and its functions.

The term “executive functions” has been applied to a wide variety of phenomena, making it difficult to formulate a commonly agreed definition. Conceptions range from early lists of classes of situations in which executive control is required [53], via distinctions between different executive functions identified by multivariate analyses of behavioral data [54] to a hierarchical organization of cognitive control in PFC [55,56]. A common denominator of these conceptions may be that executive or control functions can be voluntarily initiated to accomplish controlled sensory, cognitive and motor processing by biasing information flow through top-down signals at various levels.

In the WM literature, the most popular account of executive functions has been Baddeley’s central executive [13] that was based directly on the early conception of an attentional control system proposed by Shallice and Norman [53]. According to Baddeley [14] the central executive has not been localized to a circumscribed brain area in the model, but empirically, the functions ascribed to it have mostly been assigned to PFC. Using a latent variable approach, Miyake et al. [54] have shown that the concept of executive functions may not be monolithic but actually form a set of related, but clearly distinct executive functions comprising “inhibition of prepotent responses”, “shifting between tasks and mental sets” and “updating and monitoring of WM representations”. “Inhibition” has later been differentiated into control over PI, resistance against distracters and prepotent response inhibition, with obvious connections to interference control in WM [57]. However, there are potentially many mechanisms of how control over interfering information of diverse sources may be implemented in the brain, only few of which have been examined so far. Also it remains an open question whether or not there may be memory-specific interference control or resolution mechanisms. Miyake’s [54] executive function of “updating and monitoring of WM representations”, in comparison to the content updating studies reviewed here, may rely to a much greater degree on the continuous evaluation and implementation of changes in WM, as examined in early neuroimaging studies using the n-back task. As described earlier, in these tasks, resolution of interference, counting, discarding and encoding of information cannot be dissolved. Therefore content updating may only be partly related to Miyake’s [54] “updating and monitoring” functions. Finally, the relation of WM to “shifting between tasks and mental sets” is of utmost importance for defining both WM and executive control, as the implementation of a mental task set crucially involves the durable representation of rules. The establishment of task sets has been linked to anterior PFC [58,59], while dlPFC, posterior inferior frontal sulcus, inferior frontal junction and medial frontal cortex have been repeatedly reported to underlie switching between task sets and contextually adequate action [60,61]. Recent models have conceptualized prefrontal functions as a posterior-to-anterior hierarchy of control, reflecting increasingly abstract levels of control [55,56]. At each of these levels rules need to be represented. The question arises whether rule representations and the selection/updating of rules draw upon the same limited resources as the selection/updating of stimulus representations reviewed here. In a pioneering study, Montojo and Courtney [62] have examined this question by independently varying whether a number stimulus or a mathematical operation had to be updated in WM. Their results show that rule and stimulus information are represented in at least partly dissociable areas. Number updating yielded stronger activation changes in parietal cortex than rule updating, whereas the latter drove activity changes in the inferior frontal junction. Thus, the representation of task set and WM contents may rely on differentiable or even partly separate neural substrates. Yet, we note that this should not be

taken to presume that task set does not play a role in WM tasks: as in the classical studies by Sternberg [63] on verbal memory, most tasks on visual WM use very small sets of stimuli. Given that on each trial, all stimuli had been displayed rather recently, memory performance may not solely rely on sensory information. Rather categorically tagging items as “matches” could invoke activation in regions representing task set or stimulus–response mappings.

Taken together, the functions subserved by WM draw upon executive functions at various levels in order to control for interference and probably to represent task rules. Content updating instead may be accomplished with the mechanisms described in the earlier paragraphs. The executive function of the same name does certainly involve content updating, but performance may mainly depend on task management functions that occur in the context of n-back-like tasks.

3.2. Summary

Working memory is currently conceived as emerging from the interplay of multiple cognitive functions. In consequence, it cannot be defined autonomously, but only by identification of those basic functions that together are conceived as “working memory”. Mnemonic selection and attentional focusing form the core of Cowan and Oberauer’s [11,12] conceptions, and are subserved by dissociable neural substrates. They may also be the basic prerequisites for updating the content of WM and rehearsal. Hence, the interaction of attention and memory that is currently emphasized in the literature may suffice to explain these phenomena. However, the mediation of stability of WM by interference protection mechanisms and the unknown role of task set/rule representation in WM demand an extension of the attentional and mnemonic basis of WM by executive functions/cognitive control.

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