

Working Memory: Maintenance, Updating, and the Realization of Intentions

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“Working memory” refers to a vast set of mnemonic processes and associated brain networks, relates to basic intellectual abilities, and underlies many real-world functions. Working-memory maintenance involves frontoparietal regions and distributed representational areas, and can be based on persistent activity in reentrant loops, synchronous oscillations, or changes in synaptic strength. Manipulation of content of working memory depends on the dorsofrontal cortex, and updating is realized by a frontostriatal “gating” function. Goals and intentions are represented as cognitive and motivational contexts in the rostrolateral cortex. Different working-memory networks are linked via associative reinforcement-learning mechanisms into a self-organizing system. Normal capacity variation, as well as working-memory deficits, can largely be accounted for by the effectiveness and integrity of the basal ganglia and dopaminergic neurotransmission.

Imagine the following scenario:

You enjoy a sabbatical semester and visit a close colleague to work on a joint review paper. You have generously been offered a room on the floor where your colleague sits. One floor below, a nice library holds many texts (not accessible on the Internet) that you may want to consult when writing your review. One morning you realize that a volume in the library would be relevant for the section of the review you currently work on, and walk down only to find out that the door is locked. You head upstairs to your colleague's office to borrow her key card, and are told that the code is “1, 9, 6, 9, 3.” While rushing back down, you repeat the code silently to yourself, noticing that subtracting the last digit from the first four will give your birth year (1966). However, after you punched the code, the door will not open. Puzzled, you think you may have

entered the wrong code and try again, but the door remains locked. So you head back to your colleague and tell her that “1, 9, 6, 9, 3” did not work. She responds, “I'm sorry, that's the code for the parking garage; the correct code should be 3, 7, 4, 9, 8.” You repeat the new code to yourself while heading down, and this time it works. You enter into the library and quickly forget all about any door problems when you start to think about your section of the review and try to locate the relevant volume. You find it and bring it back to your desk and continue writing. Later on, in the afternoon of the same day, work on a new section of the review prompts you to return to the library to pick up another volume. You still have your colleague's key card and head downstairs. Once there you realize that you need the code and to save yourself from yet another stair climb you try to retrieve the code from memory. “1, 9, 6, 9, 3” pops up and you try it with no success. You think, “maybe that was



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the first code I tried (the one for the garage), but what was the correct one”?

This little scenario, which most readers may have experienced in real life in some form or another (while cooking/following a recipe, doing carpentry/construction, or while doing errands in a shopping mall), highlights several key defining features of working memory:

1. Working memory can guide behavior by means of “mnemonic representations of stimuli” in the absence of the stimuli themselves, as above when the code had to be retained in memory until the door was reached. Such active “online maintenance” of information is at the heart of the working-memory concept. The influential multi-component model of Baddeley and Hitch (1974) postulated distinct “buffers” for maintaining verbal or visuospatial information. That model further suggested that an attentional control system, the “central executive,” controls information maintenance, for example, via active rehearsal processes. The ability to maintain information in working memory can be tested in many different ways, including with delayed-match-to-sample and simple span tasks.
2. Working memory “interacts with long-term memory” in many ways. State-based working-memory models assume that maintaining information in working memory critically depends on allocating attentional resources to internal long-term memory representations (see D’Esposito and Postle 2015). Long-term memory can support the clustering or “chunking” of information in working memory (Miller 1956), as in the situation when a birth year was derived from the five digits, which can greatly reduce working-memory demands. Working memory may also rely, at least in part, on some of the same principles for information storage as long-term memory, and working-memory processes might critically contribute to the encoding and retrieval of long-term memory, as in the instance when the first code was remembered hours after it had been used.
3. Information that is maintained in working memory can be replaced with other information by means of an “updating” process, as in the case when the incorrect code (to the garage) was replaced with the correct one. Thus, successful and adaptive working memory requires both stability (when information is actively and robustly maintained) and flexibility (when information needs to be replaced and updated). Biologically based computational models have been proposed to capture these complex dynamics, and they can be taxed with tests such as running span tasks (e.g., keep track).
4. Information that is maintained in working memory can be “manipulated” or operated on by additional processes, as in the case when “3” was subtracted from “1 9 6 9” to give a birth year (1966). The possibility to actively process and manipulate information that is maintained in working memory is a salient defining feature of working memory and likely a foundation for a wide range of complex abilities. The famous reading span task (Daneman and Carpenter 1980) and related complex span tasks, such as the operation span task, all combine maintenance with the requirement to perform additional manipulation processes.
5. Working memory is essential for the “execution of a plan,” as in the example we considered above when the idea emerged to go to the library to collect a volume. In their excellent review of the cognitive neuroscience of working memory, D’Esposito and Postle (2015) recently noted that the functional characterization of working memory as underlying the ability to execute complex plans dates back > 50 years. More recently, Patricia Goldman-Rakic (1987) noted, in the same spirit, that plans can govern behavior. A particularly critical role for working memory should be in situations when the execution of a plan is interrupted, as in the scenario when the core plan of picking up a volume only could be realized after several “door-related” interruptions, and also when multiple goals are concurrently active. Inherent in



the notion of coding for the execution of a plan is motivation and incentives, and recent models try to combine cognitive and motivational control of behavior (e.g., Fuster 2013; Watanabe 2013).

Thus, working memory can narrowly be defined as temporary online maintenance of information for the performance of a task in the (near) future, but more broadly to also include manipulation and updating of the aforementioned information, as well as coordinating behavior when multiple goals are active. In the present work, we will discuss these key features of working memory from a cognitive neuroscience perspective, attempting to synthesize behavioral and neurobiological data. A variety of sources of neurobiological data will be considered, including functional magnetic resonance imaging (fMRI), molecular imaging with positron emission tomography (PET), electrophysiological registrations with electroencephalography (EEG), and magnetoencephalography (MEG), transcranial magnetic stimulation (TMS), lesion studies, cell recordings from primate neurons, and also computational modeling.

It should be stated up front that the treatment of past studies must, out of necessity, be highly selective. D'Esposito and Postle (2015) reported the results of a PubMed search on "working memory" performed late in 2014 that returned more than 18,000 results! Here, the discussion of empirical findings will be guided by a "processing-component" theoretical framework (Fig. 1; cf. Fuster 2009, 2013; see also Moscovitch and Winocur 2002; Eriksson et al. 2015). According to this framework, there is no dedicated "working-memory system" in the brain in the sense of corresponding systems for visual perception. Rather, working memory is seen as a computational and cognitive faculty emerging from the interaction among various basic processes, some of which are used in various combinations in the service of other forms of memory, such as declarative (episodic and semantic), long-term memory (cf. Nyberg and Cabeza 2001; D'Esposito and Postle 2015). In line with this framework, functional brain-im-

aging studies have found overlapping activity patterns, notably in the prefrontal cortex, for working-memory challenges, as well as for several other cognitive demands (Cabeza and Nyberg 2000; Duncan and Owen 2000; Cabeza et al. 2002; Nyberg et al. 2002, 2003; Naghavi and Nyberg 2005). The specific components of the framework outlined in Figure 1 will be presented in more detail in the next sections.

We start by discussing working-memory maintenance, including interactions between working memory and long-term memory. Next, we will discuss manipulations and updating of working memory, followed by a section on the complex topic of how intentions can be maintained and guide behavior. In the concluding section, Working Memory in Action, we will relate findings from studies of working memory at the brain and behavioral levels to variation in working-memory functioning. This will include variation among healthy younger adults, in aging and Parkinson's disease, and in psychiatric disorder.

MAINTENANCE IN WORKING MEMORY AND ITS RELATION TO LONG-TERM MEMORY

Where Is Working Memory Maintained?

In the spirit of the fundamental perception–action cycle for the temporal organization of behavior (e.g., Fuster 2013; see arrow 1 that connects the light blue [perception] and orange [action] ellipses in Fig. 1), we begin the discussion of working memory at the perception stage in which different kinds of sensory information are processed by dedicated brain systems. A long-standing basic hypothesis concerning information storage in the brain is that of "distributed storage," according to which the specific sites in the brain where information is stored are determined by how the brain was engaged during initial perception/learning (schematically shown by the overlap between the perception and representation ellipses in Fig. 1). This hypothesis is supported by studies of declarative (episodic and semantic) long-term memory (Nyberg et al. 2000; Martin and Chao 2001; Danker and Anderson 2010). Thus, when

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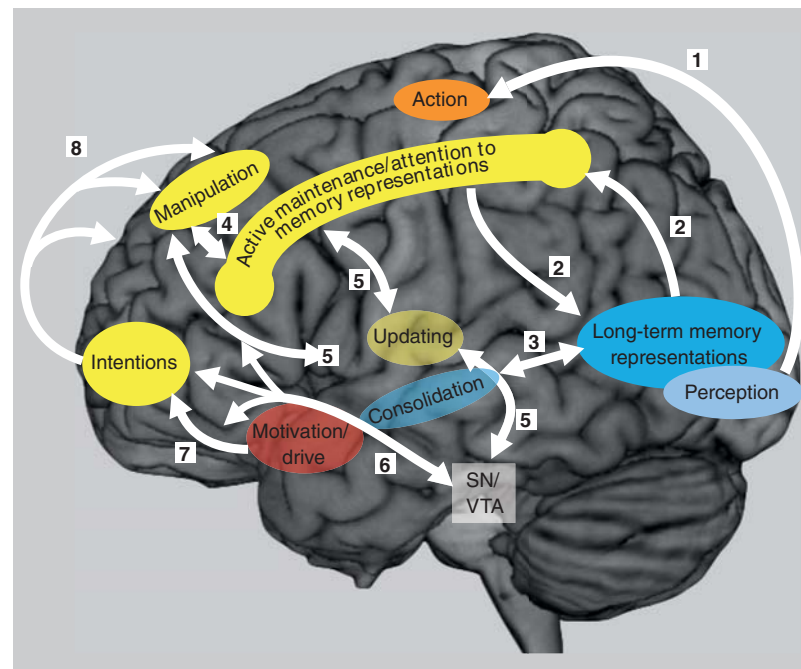


Figure 1. Working-memory processes and interactions within the perception-action cycle (arrow 1). The color-coding of processes has been freely adapted after Fuster (2013), with perception in light blue, action in orange, motivation/drive in red, long-term memory representation and consolidation in blue, and, in yellow, the working-memory processes that will be discussed. Arrow 2 represents reverberating activity in frontal, parietal, and representational areas during maintenance. Arrow 3 represents consolidation of working-memory information into long-term memory via interactions with the medial-temporal lobe system. Arrow 4 represents associations between manipulation networks, mainly in dorsofrontal cortex, and frontoparietal maintenance/attention processes. Arrow 5 represents nigrostriatal dopaminergic neurotransmission and striatocortical interactions during working-memory updating. Arrow 6 represents diffuse dopamine gating signals from the ventral tegmental area (VTA) to the frontal cortex. Arrow 7 represents emotional input to rostromedial frontal regions, and arrow 8 represents how neurons in the rostromedial frontal cortex, coding for cognitive and motivational context, influence other working-memory networks to support goal-directed behavior. Transparency of ellipses indicates major subcortical nodes for updating (striatum), consolidation (hippocampus), and motivation (amygdala, brain stem, hypothalamus). SN, Substantia nigra.

a long-term memory is retrieved, some of the perceptual regions that were recruited during learning become reactivated in a material-specific sense.

A similar principle seems to hold true for maintenance of working memory. That is, in the context of working-memory maintenance, attention to semantic representations (e.g., letters and digits), as well as sensorimotor representations (e.g., colors, line orientations), have been found to engage material-specific brain areas. In particular, analyses of fMRI data by means of multivariate “pattern analysis” techniques have

revealed that modality-specific regions retain sensory-specific working-memory representations during the delay period (see Sreenivasan et al. 2014). Also, if TMS is applied to visual cortex during maintenance of visual information, there is a reduction in the performance of working memory (van de Ven et al. 2012). Collectively, these and related studies converge to suggest that the maintenance of working memory does not rely on any specialized storage “buffers,” but instead shares the same representational zones as retrieval from long-term memory.

How Is Information in Working Memory Maintained?

How, then, is activity in neuronal representational populations maintained during a working-memory delay? In the scenario above, this concerns how the five-digit code was upheld in working memory from the time when it was heard (perception) to when the code was used (action). Similarly, the majority of working-memory studies involve online information maintenance over a few seconds. As discussed in *Where Is Working Memory Maintained?*, we would predict that posterior cortical neuronal populations engaged in the representation of digits will be involved, but also the prefrontal cortex. Recordings by Joaquín Fuster of cells in the primate cortex (Fuster and Alexander 1971; see also Fuster 2013) revealed that cells in the frontal cortex showed sustained activity during a working-memory delay. Subsequently, such cell populations have been discovered outside the frontal cortex as well, and persistent neural activity in frontal and select posterior neuronal populations jointly define working memory for a specific type of stimulus. These kinds of memory networks, or cognits (see Fuster 2013), are established by means of associative principles when the participating cell populations jointly become active during the performance of a task (later, we will return to the issue of memory networks being related to other kinds of networks, for example, those representing contextual information).

Cells in one and the same zone of the frontal cortex may contribute to working memory of different kinds of information by interacting with select posterior cell populations. Thus, the frontal cortex is likely not a storage buffer per se but exerts top-down control of other neuronal populations in the network that actually represent information (for discussions about material specificity in frontal maintenance activity through posterior feedback signals, see, e.g., Sala and Courtney 2007). Typically, along with the frontal cortex, superior parietal regions also show elevated sustained activity during the delay period, suggesting that parts of the parietal cortex may serve general top-down

functions (e.g., sustain attention to internal representation; see Fig. 1). Likely, there are multiple sources (frontal, parietal, other) of top-down signals to lower-order areas (see arrow 2 from the yellow maintenance ellipse in Fig. 1 to the blue representation ellipse), which jointly contribute to maintenance of specific representations via persistent activity (cf. D'Esposito and Postle 2015).

If the top-down signal is interfered with, for example, by local cooling of the lateral frontal prefrontal cortex, this has a negative impact on posterior activity, as well as on performance, and comparable effects are seen after cooling of posterior cortical sites (see Fuster 2013). One likely interpretation of the findings of such cooling experiments, in which nodes of a distributed memory network are inhibited, is that it interrupts reentrant loops between frontal and posterior cortical zones that maintain information in working memory by reverberation (see double arrows 2 that form a circuit in Fig. 1).

Synchronous oscillations also offer a basis for how distributed brain regions in frontal, parietal, and posterior cortices might interact in the service of working-memory maintenance. In an MEG study, Jensen and Tesche (2002) examined maintenance of visually presented digits in an experimental protocol in which the memory load was parametrically varied between one and seven items. During a 3-sec maintenance period, they found ongoing θ activity over frontal sensors, and this θ activity changed in relation to the number of items maintained in working memory. The investigators suggested that the elevated θ activity resulted from sustained neuronal activity related to active maintenance of memory representations. This interpretation is supported by the findings from a study that examined interactions between frontal cortex and a posterior cortical region, V4 (Liebe et al. 2012). During the maintenance period, these two areas showed synchronized local field potentials in the θ range. Oscillations in other frequencies may also be relevant, such as in the γ band (Roux and Uhlhaas 2014).

A complementary mechanism by which working memories may be maintained is via rapid changes in synaptic weights (Barak and

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Tsodyks 2014). Neuronal (Rainer and Miller 2002) and fMRI (Lewis-Peacock et al. 2012) recordings have shown that elevated persistent activity may not always characterize the working-memory delay phase—and still behavior can be successful. Moreover, the metabolic demands of persistent-activity coding are high (Mongillo et al. 2008). Synaptic plasticity as one basis for working memory has been incorporated in various forms in computational models (e.g., O'Reilly et al. 1999) based both on non-Hebbian (Mongillo et al. 2008) and Hebbian (Lansner et al. 2013) synaptic plasticity.

Does Working-Memory Maintenance Promote Long-Term Memory Formation?

The formation of new declarative long-term memories is critically dependent on the mediotemporal/hippocampal brain system and a cascade of cellular events, including long-term potentiation (LTP) (see Squire and Kandel 2000). Relatedly, a computational model has been suggested in which synaptic weight changes in the hippocampus underlie working-memory encoding and subsequent maintenance (O'Reilly et al. 1999; see also Hasselmo and Stern 2006; Fiebig and Lansner 2014). There is imaging evidence that the hippocampus is engaged during working-memory maintenance under certain circumstances, such as during maintenance of novel information (e.g., Ranganath et al. 2001; Cabeza 2004), and a recent high-resolution fMRI study of mediotemporal lobe (MTL) subregions provided evidence that neurons in these regions may act as a working-memory buffer for novel information (Schon et al. 2015). In the introductory hypothetical scenario, the first code was retained hours later, and some studies have linked working-memory-related brain activity to subsequent long-term memory and found that parahippocampal-sustained fMRI activity during active maintenance was correlated with later memory performance (Schon et al. 2004; Axmacher et al. 2008; see also Rudner et al. 2007; for related intracranial EEG evidence, see Axmacher et al. 2007). Relatedly, findings by Ben-Yakov and Dudai (2011) show that poststimulus hippocam-

pus activity contributes to the registration into long-term memory of complex real-life information.

Thus, maintenance of novel information in working memory can lead to the formation of new long-term memories by engaging the MTL “consolidation” system, which is consistent with the current processing-component framework postulating shared stores for working and long-term memory. The possibility that working-memory processing leads to long-term memory formation is shown by arrow 3 between the “representation” and “consolidation” ellipses in Figure 1. At the same time, it must be noted that patients with MTL lesions can perform well on tests of working-memory maintenance, even when the task situation requires binding of items with locations (Allen et al. 2014), but they show impairment if the material to be learned exceeds working-memory capacity (Jeneson and Squire 2012). These data highlight the dynamic relation between working memory and long-term memory. At subspan challenges, an intact MTL system is not a prerequisite for working-memory maintenance, which, however, does not preclude the possibility that the MTL system becomes engaged and information encoded into long-term memory in individuals with no MTL lesions. At supraspan challenges, the core working-memory maintenance system is insufficient for supporting performance, so long-term memory processes and an intact MTL system become vital. Further work will be crucial for elucidating the factors that influence whether information maintained in working memory becomes consolidated into long-term memory (see, e.g., Wagner 1999; Jensen and Lisman 2005; Sneve et al. 2015).

HOW CAN INFORMATION IN WORKING MEMORY BE MANIPULATED AND UPDATED?

Frontal Cortex and Working-Memory Manipulation

Until now, we have discussed the role of frontal cortex in the maintenance of working memory in terms of providing a source of top-down signals to posterior cortical areas involved in long-



term memory storage. Some models hold that ventrocaudal frontal zones (BA 44, 45, 47) constitute the main loci where maintenance signals are generated (Smith and Jonides 1999; see also Pudas et al. 2009), whereas other findings indicate that maintenance can be supported by both ventro- and dorsolateral frontal regions (e.g., Postle et al. 1999). To the degree that vast portions of the frontal cortex can contribute top-down maintenance signals, along with other “sources,” such as the parietal cortex and hippocampus (Fuster 2013), one might predict that restricted frontal lesions will not profoundly impair the performance on simple maintenance tasks, such as digit-span forward. This prediction is supported by the results from human lesion studies showing that frontal lesions have weak or no negative effects on simple working-memory maintenance (e.g., Volle et al. 2008; Barbey et al. 2013). In contrast, frontal lesions, notably in the dorsolateral cortex, have marked impact on working-memory manipulation operations, and functional imaging studies have shown elevated dorsolateral prefrontal activity as a function of the complexity of working-memory operations (e.g., Nagel et al. 2009; Nyberg et al. 2009b). It should be stressed that increased complexity can be instantiated by using tasks that require that some operation is performed on the information that is maintained in working memory (e.g., letter–number sequencing or digit-span backward) or by increasing the number of items that have to be maintained (as in Sternberg type of tasks). Both of these procedures have been associated with elevated dorsolateral prefrontal activity (Veltman et al. 2003). Increased dorsolateral activity when maintenance gets harder likely reflects the use of manipulation processes (cf. Rypma et al. 1999), such as attempts at chunking (cf. discussion above about working-memory and long-term memory interactions).

Thus, in the literal sense of the working-memory concept (cf. Moscovitch and Winocur 2002), the role of the prefrontal cortex is particularly salient when the situation actually requires one to work with the content of memory—not only passively hold it (the latter is sometimes referred to as “short-term memo-

ry”). In the spirit of the processing component framework (Fig. 1), one may ask whether distinct frontal regions become engaged depending on the specific “kind” of manipulation process that is engaged by a given task. There is some meta-analytic evidence for regional specificity, including interactions between manipulation demand and material type (Wager and Smith 2003). However, a more recent meta-analysis of 36 event-related fMRI studies found only limited support for specificity (Nee et al. 2013; see further the updating section below). Instead, it found that four manipulation processes (protect from external distraction, prevent intrusion of irrelevant memories, shifting of attention, and updating the contents of working memory) engaged several overlapping frontal regions. Sites of strong convergence were observed in widespread medial and lateral frontal cortex, including the middle frontal gyrus and the caudal superior frontal sulcus (illustrated by the yellow “manipulation ellipse” in Fig. 1), and also regions of parietal cortex that form anatomical circuits with prefrontal cortical regions. The superior frontal activation was assigned an attention function, possibly of a spatial nature, that should characterize all four forms of manipulation processes examined.

Lesion studies provide converging support for a general role of the mid-dorsolateral prefrontal cortex (Petrides 2000), medial prefrontal cortex/anterior cingulate (Mesulam 1981), and parietal cortex (Koenigs et al. 2009) in working-memory manipulation, including conflict monitoring (see Botvinick et al. 2001). Prefrontal and parietal cortex regions form circuits with cerebellar regions, and both imaging studies (Stoodley and Schmahmann 2009; Marvel and Desmond 2010) and studies of patients with brain damage (Malm et al. 1998) implicate the cerebellum in working-memory manipulation. Moreover, a frontostriatal–cerebellar circuit is thought to have a general control function in resource-demanding long-term and working-memory tasks (Marklund et al. 2007a).

The notion of a “general control system” that becomes more engaged under challenging working-memory manipulation conditions is in good agreement with the proposition by Bad-

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deley and Hitch (1974) that an attentional control system (the “central executive”) guides various kinds of working-memory storage (cf. Awh et al. 2006). Importantly, however, the instantiation of manipulation networks, general as well as more specific ones, is likely not via some form of superordinate executive or regulator. Instead, as long as the task poses only limited challenges (e.g., a forward digit-span task with maintenance of three to four items), it can be performed without much executive control or manipulation operations, but if the situation changes into a more demanding one (e.g., change to “backward” digit-span or supraspan levels), relevant manipulations will be triggered by means of association, which translates into the orderly activation of networks and their subnetworks within and outside of the frontal cortex (Fuster 2013). This principle is shown by the reciprocal arrow 4 in Figure 1. The much more prolonged developmental trajectory for manipulation versus maintenance processes (Crone et al. 2006), in addition to structural maturation of relevant brain areas and connections, could reflect the gradual establishment of associative networks that can support complex goal-directed behavior.

A Subcortical Dopaminergic Updating System

Stable maintenance of information in working memory is imperative for goal-directed behavior, but so is flexible and rapid updating of the contents of working memory. The necessity of a dynamic relation between maintenance and updating has been captured in terms of a “gating mechanism”; a closed gate promotes maintenance, an open gate allows updating. There is evidence from functional imaging that parts of the frontal cortex are more active during working-memory updating relative to other forms of working-memory manipulation, such as inhibition (Dahlin et al. 2008) and shifting of attention (Nee et al. 2013). However, it has been argued that it is only through interactions with the basal ganglia that the prefrontal cortex realizes this gating function (O’Reilly 2006), such that the striatum provides gating signals to the frontal cortex (Go/update or NoGo/

maintain) via interactions with the thalamus and the substantia nigra. In support of this model, fMRI studies have observed striatal activity during working-memory tasks that involve updating (Lewis et al. 2004; Dahlin et al. 2008), and high-resolution fMRI of the mid-brain revealed activation in or near the substantia nigra (D’Ardenne et al. 2012). Relatedly, frontostriatal interactions have also been implicated in the control of access to working-memory storage (McNab and Klingberg 2008), which may contribute to interindividual differences in working memory. We will return to the latter issue in the concluding section of this review. Working-memory updating is illustrated by arrow 5 in Figure 1, connecting the brain stem (substantia nigra), the basal ganglia (striatum), and frontoparietal cortices.

A related model for updating includes a dopamine-based gating mechanism (Braver and Cohen 1999; Durstewitz et al. 2000; Cools and Robbins 2004; see also Gabrieli et al. 1996; O’Reilly 2006). The neurotransmitter dopamine has long been implicated in higher-order cognitive functions, such as working memory (e.g., Williams and Goldman-Rakic 1993). The two major dopamine receptors, D1 and D2, have been associated with distinct working-memory functions (Grace 2000; Cohen et al. 2002). The extrasynaptic D1 receptor has been linked to tonic (sustained) dopamine action and maintenance in working memory, whereas the synaptic D2 system is implicated in phasic (transient) dopamine functions that are relevant for flexible updating of working memory. Updating gating signals take the form of phasic bursts of dopamine that activate D2 receptors and destabilize the maintenance state that is upheld by lower concentrations of tonic dopamine D1 firing. This can happen through gating signals from the ventral tegmental area to the prefrontal cortex (mesocortical pathway; arrow 6 in Fig. 1), but also through the nigrostriatal pathway (Fig. 1, bottom arrow 5). Indeed, the relative density of D2 receptors is much higher in the striatum than in the frontal cortex, making dopamine D2 action in the striatum well suited to serve a gating function (Hazy et al. 2006; Cools and D’Esposito 2011). Correspondingly, PET



imaging during a letter-memory updating task revealed that working-memory updating affects striatal D2 binding (Bäckman et al. 2011).

Via the mesolimbic dopaminergic pathway, dopamine can also influence long-term memory formation (e.g., Lisman et al. 2011), and partly overlapping frontostriatal circuits have been shown to be implicated in updating of long-term memory as they have for working memory (Nyberg et al. 2009a). There is evidence that updating of long-term memory involves adding extra information to already existing memory networks rather than overwriting the older preexisting information (Eriksson et al. 2014). Similarly, by using a three-back working-memory task it was shown that no-longer-relevant items (presented more than three items back) still interfered with ongoing processing (Gray et al. 2003). Thus, although the working-memory content had been updated so that these items no longer were actively maintained, they still resided in memory to the degree that they could influence performance. These and related observations indicate that working-memory updating makes old information less accessible but not “erased,” possibly because “familiarity” effects from previously but not currently maintained information can be supported by long-term memory.

MAINTAINING AND REALIZING INTENTIONS

In the preceding section, we discussed a gating mechanism for maintaining and updating the contents of working memory, which begs the question of how the decision is made as to when to open or close the gate? In turn, this question relates to the more general topic of how goals and intentions are formed, maintained, and updated in working memory, and how they can influence and guide more basic working-memory operations. These complex questions map on to several aspects of our introductory scenario and, in particular, to the ability to maintain the goal from when the plan was formed to when it finally was realized—despite the many interfering and distracting events that happened in between. Indeed, as

has been emphasized by Fuster (2013), the concept of working memory goes well beyond the act of maintaining discrete information (as in a laboratory delayed matching to sample (DMS) task or maintaining the code in our introductory example) to networks that represent the task, the objective, and the current specific context. All of these networks will be linked by association (Asaad et al. 1998; see Fuster 2013) and recruited to various degrees depending on the complexity and familiarity of a given task and context. If, as in the introductory example, the situation is unfamiliar or there are interruptions to the execution of a plan, the highest integrative networks involving rostro-prefrontal cortex (the “intention” ellipse in Fig. 1) become engaged (Fuster 2013; for similar hierarchical views on frontal cortex functional organization, see, e.g., Christoff and Gabrieli 2000; Lepage et al. 2000; Braver and Bongiolatti 2002; Koechlin et al. 2003; Ramnani and Owen 2004; Koechlin and Summerfield 2007; Badre and D’Esposito 2009).

One source of evidence that task context is coded by the prefrontal cortex comes from findings that prefrontal neurons show differential pre-cue baseline activities depending on the task situation (e.g., Wallis et al. 2001; see Watanabe 2013). Such findings are consistent with a view that frontal neurons monitor and maintain the currently relevant cognitive context (cf. Miller and Cohen 2001). Functional imaging studies contribute converging evidence by showing that rostro-prefrontal regions code for the nature of future processing (Sakai and Passingham 2003) and that frontopolar regions show a sustained activation profile throughout a task—even when no stimuli are present (Marklund et al. 2007b; see also Velanova et al. 2003; Dosenbach et al. 2007). Also, frontopolar regions have been implicated in prospective memory (Burgess et al. 2003) and in forming new intentions (Kalpouzos et al. 2010). Collectively, these kinds of findings link the rostrolateral cortex to prospective coding of the cognitive context in a given situation.

Relatedly, prefrontal neurons are involved in coding the motivational context of a task (see Watanabe 2013), for example, as induced by

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different kinds of rewards (Wallis and Kennerley 2013). Reward signals from the orbitofrontal cortex can influence the current cognitive context via lateral prefrontal neurons. More generally, the orbitofrontal cortex is a site where emotional signals from the brain stem, amygdala, and the hypothalamus can interact with the cognitive processing of the perception–action cycle (arrow 7 in Fig 1; cf. Fuster 2013). By affecting updating of task-context representations (D’Ardenne et al. 2012) and by driving associative reinforcement-learning mechanisms (Schultz 1998), dopamine also plays a key role in this context. A dual role for dopamine in gating and learning opens up for a self-organizing system that learns when to update goals and contexts to maximize rewards and minimize punishments (cf. Miller and Cohen 2001; McClure et al. 2003; see also Jonasson et al. 2014). The self-organizing nature of executive control processes is also emphasized in Fuster’s (e.g., 2013) associative perception–action cycle. As such, there is no need for “a controller of the control processes,” and avoids the concept of a “homunculus.”

Thus, the intention to go and get a reference text (or a cup of coffee) while writing a paper can be elicited via bottom-up input from the internal milieu or by associative mechanisms, and its subsequent successful realization is dependent on neurons in the rostrolateral cortex that code the current cognitive and motivational contexts. Prefrontal context representations can be updated by dopamine signals and strengthened by reinforcement if they lead to successful outcomes. The rostrolateral cortex (area 10) has diffuse and extensive nonreciprocal projections with more caudal frontal regions (see Badre and D’Esposito 2009) and forms functional networks with dorsofrontal and parietal regions (Vincent et al. 2008). These patterns of connectivity allow rostrolateral cortex to affect processing in other networks that maintain, update, and manipulate information (represented by arrow 8 in Fig. 1). Anterior goal networks may influence other networks by means of synchronous oscillations (Voytek and Knight 2015; Voytek et al. 2015; see also Engel et al. 2001; Cavanagh and Frank 2014),

possibly in conjunction with the thalamus (Saalmann et al. 2012). “Stepwise” feedback signals in the hierarchical frontal pathways to the rostrolateral cortex (cf. Badre and D’Esposito 2009) could contribute to maintaining the current goal. When the realization of an intention is much delayed and/or interfered with by various distracting events, long-term memory processes will be critical for reactivating the relevant frontal goal representations based on sensorimotor cues (Rainer et al. 1999; cf. Miller and Cohen 2001; Kalpouzos et al. 2010).

WORKING MEMORY IN ACTION

In this final section, we briefly consider how the present view of working memory, schematically outlined in Figure 1, can be related to normal variation in working-memory functioning, as well as working-memory deficits induced by aging and disease. Consider first normal variation in the capacity of working memory. A characteristic feature of working memory is limitations on how much information can be retained at any given time. Average capacity has been estimated to be 3–4 items in young, healthy individuals (Cowan 2001), but exactly “how” much information depends on a number of factors, including how well the information can be related to preexisting representations that can serve as “schemas.” For instance, in the opening example, the first access code could be linked to a birth year. Such mnemonics can greatly increase how much information can be retained. In a sense, then, any claim for a fixed capacity will be somewhat artificial in that it depends on what processing components are allowed to be at play (Saults and Cowan 2007). Individual differences in working-memory capacity on simple, as well as more complex tasks, have received much attention as they have been related to basic intellectual abilities, such as general intelligence (Kane and Engle 2002; Gray et al. 2003; Fukuda et al. 2010), and found to predict real-world achievements, such as learning math (De Smedt et al. 2009; see Raghobar et al. 2010) and school grades (Cowan et al. 2005).

Working memory is tightly linked to a frontoparietal cortical network (see Fig. 1) and pari-



etal activity correlates strongly with load and plateaus when capacity limits are reached (Todd and Marois 2004; Vogel and Machizawa 2004). Also, parietal activity increases when distracting information is unintentionally encoded into working memory, which is more likely to happen to individuals with lower capacity (Vogel et al. 2005). McNab and Klingberg (2008) found that parietal load effects, reflecting unnecessary storage of distractors, were negatively correlated with basal ganglia activity. They further showed that prefrontal and basal-ganglia activity was positively associated with capacity. Collectively, these findings suggest that one determinant of working-memory capacity is how efficiently an individual can exert control over the encoding of working memory, and how frontostriatal regions serve a gatekeeping function in this regard. Clearly, this function resembles the dopaminergic gating function discussed above in the context of updating, and McNab and Klingberg (2008) also note the potential role of dopamine in gating access to working memory. Evidence for a link between working-memory capacity and dopamine also comes from human PET studies (Cools et al. 2008) and genetic (e.g., Bilder et al. 2004) and pharmacological (e.g., Garrett et al. 2015) studies (for a comprehensive review, see Cools and D'Esposito 2011).

Dysfunctional dopamine neurotransmission may, at least in part, account for working-memory deficits in aging (Karlsson et al. 2009; Fischer et al. 2010; Nyberg et al. 2014; see Bäckman et al. 2010) and in Parkinson's disease (Marklund et al. 2009; Ekman et al. 2012). Dopamine has also been implicated as a source of working-memory difficulties in schizophrenia (Cohen and Servan-Schreiber 1992; Goldman-Rakic 1999; Castner et al. 2000; Abi-Dargham et al. 2002), attention-deficit/hyperactivity disorder (Castellanos and Tannock 2002; Martinussen et al. 2005; Sagvolden et al. 2005), and other psychiatric and neurological conditions (see Maia and Frank 2011).

Thus, the networks we have outlined herein (see Fig. 1) may be of fundamental importance for adequate functioning in a variety of situations. The disturbance of dopaminergic neurotransmission may be a common basis

for deficits in higher-order cognition in many conditions. Cognitive interventions have shown some promise in modulating dopamine D1 and D2 systems (McNab et al. 2009; Bäckman et al. 2011; for reviews, see Klingberg 2010; Bäckman and Nyberg 2013). We are currently exploring the potential role of long-term physical interventions in strengthening dopamine and related cognitive functions, and psychopharmacological approaches hold promise in this regard (Wang et al. 2011). An important task for future research is to examine further ways of supporting deficient working-memory networks, as this in turn may influence significant aspects of everyday functioning.

CONCLUSIONS

In this review, we have argued that working-memory maintenance is the result of directing attention to semantic or sensorimotor representations. This process can be realized as persistent top-down signals from the frontal cortex and other sources to lower-order areas, and synchronous network oscillations and rapid changes in synaptic weights may also contribute to maintenance. Although attention is central to working memory, specific working-memory functions may be performed with little or no attentional processing. For example, integrating pieces of information to be maintained in working memory (i.e., "chunking") can be relatively unaffected by attention-demanding concurrent tasks (Baddeley et al. 2009), and there are demonstrations of short-term maintenance of information made nonconscious by diverting attention from the target (Bergström and Eriksson 2014). The details of when and how attention is critical for working-memory processes should be further specified in future research.

The concept of working memory goes well beyond the act of maintaining discrete information to networks that underlie manipulation and updating of the contents of working memory, as well as to networks that represent the task, the objective, and the specific context. All of these networks are linked by association and are differentially recruited depending on the current demands.

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