Can we distinguish three maintenance processes in working memory?

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Abstract

We describe three mechanisms—consolidation, refreshing, and removal—defined in several theoretical reviews in a recent *Ann NY Acad Sci* special issue as processes that may serve to strengthen new memories. We detail their explicit and implied differences and similarities, and highlight points upon which theorists disagree about their supposed characteristics. We consider the challenges remaining in refining definitions of these processes and with situating them within working memory theories, and consider how these process definitions and theory should restrict each other.

Keywords: working memory; refreshing; consolidation; removal; short-term memory; forgetting

Three distinct maintenance processes have been proposed in recent years to assist maintenance in working memory, the limited-capacity system for mentally holding information in readiness for imminent use. *Consolidation* serves to stabilize novel information; *refreshing* boosts activation of information, preventing its otherwise inevitable loss; *removal* de-activates information that was once activated in working memory, freeing limited resources for activating different information. For the first

time, teams of scholars who study working memory have attempted to comprehensively and consistently define these concepts in several theoretical articles featured in a recent special issue of *Annals of the New York Academy of Sciences*, products of a symposium that also produced other, empirically-oriented articles on these maintenance processes.[1] After the symposium, lingering disagreements on the definitions remain substantial among the theoretical articles, as we would expect given that consolidation and removal have not been discussed much in this field until fairly recently. Uncovering these disagreements and making them explicit allows researchers to better understand where the gaps in our collective thinking lie. In the theoretical articles, points of remaining disagreement about each concept are delineated. Our aim here is to consider these proposed processes together, highlight their commonalities and discrepancies, and situate them within models of working memory in a way that might motivate future research. We do so with special reference to the three special issue review articles on the concepts of consolidation[1], refreshing[2], and removal[3].

Each process, as applied to working memory, is imagined to operate on representations in which an item is bound to its context (e.g., spatial location, serial position), or perhaps when novel perceptions must be more firmly established by linking them to long-term knowledge[2]. The processes could differ as to when they are initiated, how long they take to complete, whether they monopolize attention, and whether they are under conscious control. However, because there remains substantial disagreement within each concept's definition, it remains unclear how distinct these processes are. Furthermore, the processes' definitions sometimes depend on underlying

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theory on which disagreement remains, (e.g., are maintenance-supporting functions needed because information would decay otherwise[4] or in order to prevent interference?[5]). We shall make two pair-wise comparisons—between consolidation and refreshing, and between refreshing and removal—to further explore similarities and differences between the processes. Ultimately, we think that the definitions are still works in progress that do not always perfectly distinguish one process from another, yet we hope that this exercise will help to focus new research aimed at clarifying how we remember.

Though naturally many tasks are used to measure maintenance enhancement processes, we shall illustrate similarities and differences between the processes via the complex working memory span paradigm, because it has been used to measure each process, is thought to index individual differences in working memory well, and provides ample opportunity for the operation of the three processes to be observed. In a complex span task, participants are given a sequence of items to remember, interleaved with attention-demanding choice judgments. Making these discriminations is believed to require attention, thereby starving any other process of attentional resources. For instance, in a typical complex span task participants might be given a word to remember, then asked to discriminate whether a sentence is veridical or not, then given another word to remember, then another sentence to judge, and so forth. There can be multiple processing episodes or a single episode between each two memoranda. After a sequence of 2-8 to-be-remembered item presentations and processing judgments, participants attempt to recall the items in serial order. Maintenance enhancement processes of some kind may be inferred from performance on this task in several ways: by measuring how much is remembered as a function of the time provided to perform

the discrimination judgments[6], by measuring how long it takes to perform the discrimination judgments as a function of how many items are currently maintained[7–11], by measuring memory performance as a function of the amount of time inserted between each trial[12].

The purpose of complex span procedures originally was to ensure that both storage and processing aspects of working memory were engaged because capacity during processing was considered to reflect how working memory is used in real-life activities such as reading and math[13,14]. As evidence grew indicating that processing and storage may share general, attentional resources[15], another goal was to use the processing task to control the amount of attention available for mnemonic activities[16,17] and to observe the effect of mnemonic activities on processing[7,18]. We shall turn to evidence from tasks like this as we compare definitions of each maintenance process and the procedures for manipulating and measuring them, because considering the maintenance processes within a specific task context elucidates the lingering ambiguities that still prevent us from establishing distinct operational definitions of each process. Ultimately, we think that refining the definitions of these processes benefits greatly from considering two (or more) of them jointly within the same experimental designs[6,12,19].

Consolidation and refreshing

The operational definitions of consolidation and refreshing are remarkably similar even though their raisons d'être differ. Both are meant to be applied to a wide range of stimulus types, unlike verbal rehearsal, which applies only to verbalizable information and seems to be differentially affected by manipulations that limit articulation[20].

Conceptually, consolidation and refreshing seem like they could be distinct, in that consolidation firms up new, unstable perceptual representations while refreshing prevents the loss of information already more persistently established in mind. Indeed, consolidation has been invoked to explain phenomena that would not be attributable to refreshing, such as identification of targets in attentional blink paradigms[21]. Both processes are generally believed to be intensive: being engaged in consolidation prevents encoding of incoming information[22] and similarly, it is assumed that refreshing cannot occur effectively during another attentive process[1]. One could think of consolidation and refreshing as a two-stage process, by which information must be consolidated to some degree in working memory before it could be eligible for refreshing. However, consolidation and refreshing in working memory are usually operationalized in exactly the same way: by varying the amount of uninterrupted time inserted after some key trial event. Crucially, to measure consolidation this uninterrupted time should occur immediately after the to-be-remembered information, whereas to measure refreshing, the free time may occur at any point after the to-be-remembered information has been presented, until the to-be-remembered information is forgotten beyond recovery, including immediately after presentation of a memory item. Distinguishing whether refreshing and consolidation could be distinct therefore depends on separately evaluating the effects of imposing free time at these various moments after presentation of a memory item. They could be independent processes or they could be reciprocal in the sense that as more consolidation occurs, the rate of memory loss becomes slower and less refreshing is necessary to preserve the representation[23,24].

Evidence indeed suggests that the free time inserted immediately in between presentation of the memory item and presentation of the to-be-processed item is special. Bayliss, Bogdanovs, and Jarrold[19] varied the amount of free time in this interval, while keeping total time constant by manipulating whether a long interval was placed before or after the to-be-processed stimulus. They also manipulated the cognitive load of the subsequent processing task in order to independently vary the effectiveness of attentional refreshing that occurred later during retention. They consistently observed effects of placement of the processing task, such that allowing more uninterrupted time immediately after the memory item improved recall, and they also found better recall with the easier processing task. These factors did not interact, which suggests that the manipulations of processing placement and cognitive load affected different processes. De Schrijver and Barrouillet[6] similarly compared effects of the duration of free time provided immediately after presentation of the memory item with effects of the cognitive load of the processing task, and likewise found that these effects typically did not interact; they only observed an interaction when they included a condition in which no time was allowed for consolidation, presumably because in this condition, so much of the list was forgotten under high cognitive load. That manipulations of the duration and position of free time consistently do not interact supports the idea that even if the processes are quite similar, consolidation of novel information may differ from the process used to enhance maintenance of stable representations.

The complementary results from these two studies[6,19] suggest that disrupting the use of free time and the temporal position of free time both affect recall performance, presumably because the manipulations independently affect only one of the maintenance-enhancing processes. While this is plausible, it also remains possible that

one process, performed at different moments, has different impact. The latest thinking on consolidation and refreshing, as reflected in this volume, identifies only the temporal placement of the process with respect to encoding of the memoranda as a unique way to operationally differentiate between consolidation and refreshing. Another possible difference is the time the process requires to be adequately performed: refreshing is believed to occur quite rapidly, on the order of tens of milliseconds, whereas consolidation is believed to require at least 500 ms, and likely longer. However, even this point remains unclear because of suggestions that there are two kinds of refreshing, a quick process and a slow process[2], and others note that consolidation and refreshing could be interchangeable with each other, accomplishing the same purpose[6], or inter-dependent, such that the quality of consolidation affects the progress of subsequent maintenance processes[23,24]. Since the theoretical descriptions of consolidation and refreshing are so similar, presumably the two processes may enhance memory in similar ways, begging us to question whether we are truly describing distinct processes, particularly consolidation and a hypothetical slow refreshing operation.

One advantage of distinguishing between consolidation, which must occur to a certain extent before the information can be recalled, and a post-consolidation strengthening process like refreshing is that the distinction could help to better explain why for some stimulus types, little or no effects of cognitive load during retention are observed. These effects have been taken to mean that refreshing is not happening with some stimuli, leading to claims that some materials (e.g., unfamiliar visual characters[25] or fonts[7]) cannot be refreshed. Perhaps instead, unfamiliar information requires more time or exposure to be sufficiently consolidated[26], and poorly consolidated information of any sort cannot be refreshed. In any case, it is unclear from the currently available

evidence whether so-called “unrefreshable” representations were ever sufficiently consolidated; one might instead suggest they are “unconsolidateable”, except that presumably, anything was at some point so novel and unfamiliar to any individual that it could not be absorbed quickly. This vision of the two processes (or acknowledgement of the distinct timescales at which maintenance enhancement must operate) seems to us superior to limiting refreshing by declaring that it can only occur for certain stimulus types (while also maintaining that it is nonetheless a general, rather than a domain-specific, process[2,4]). One could also still suggest that a single enhancement process is in effect, but that it is particularly necessary to be applied immediately after encoding for unfamiliar items.

It might be possible to achieve more clarity by considering multiple traits of the attentional system[27,28]. Attention always implies that one mental activity takes place at the expense of another potential activity, but not all attended activities are voluntary; sometimes, an obligatory activity captures attention. It is possible that some degree of consolidation is obligatory and determined by stimulus events (such as the amount of free time available following the stimulus[29]) but prevents other mnemonic uses of attention until it is completed. By analogy, one must catch a ball before one can choose what else to do with it (e.g., throw it in the air or bounce it).

Refreshing and removal

A methodological difficulty in dual-task procedures is that the effect of one task on another can be attributed either to a limitation in available resources shared between the two tasks, or to interference from the stimulus materials of one task on the memory representations needed in the second task. Whereas the consolidation and refreshing

hypotheses presuppose a limited resource, the alternative supposition that there is interference between task materials leads to the removal hypothesis, the notion that attention is needed to prevent processing materials from intruding into the episodic representation of the memoranda. Like consolidation and refreshing, removal is manipulated by altering the duration and position of free time within the confines of a working memory task. For removal to occur, free time must be available at any time after presentation of the information that needs to be removed. In the complex span paradigm, to-be-processed distractors that are confusable with the memory items are plausible targets for removal. Oberauer and Lewandowsky[12] tested whether assuming removal of processing task content, rather than refreshing of memoranda, accounted for superior recall in the complex span paradigm. By using words as both memoranda and distractors, it was possible to observe the rates at which distractors intruded into recall (and thus were definitely *not* removed from working memory). They manipulated the time following each processing episode, assuming that more time would correspond to more complete removal, and therefore better recall of memoranda, including fewer distractor-word intrusions. Indeed, with more time after the distractors, memory performance improved. This improvement could not be attributed to refreshing as well as removal because with less time after distractors, participants erroneously recalled more of the distractors despite having less time to refresh the memoranda or the distractors. Moreover, Oberauer and Lewandowsky further showed that increased time following distractors improved memory recall and reduced distractor intrusions even in a paradigm in which all of the processing episodes were presented before any of the memoranda. In that case, the time could not be used to consolidate or refresh the memoranda; any maintenance operations performed during the free time could only

have been performed on the processed distractors. This cleverly demonstrates a distinction between time being used to diminish no-longer-relevant as opposed to boosting still-relevant information.

It is important to point out that distractor removal probably cannot completely replace both consolidation and refreshing as mnemonic mechanisms (see, e.g., [30,31]). Oberauer and Lewandowsky[12] used distractors that were similar to the verbal items to be remembered, allowing intrusions, and found little additional interference when they interposed a spatial task between distractors (attributed to interference with the removal process itself). Removal probably cannot explain why there is a decline in performance when the only distraction task consists of that same spatial task interpolated between verbal items to be remembered, that is, when there is nothing confusable with the memoranda that would need to be removed from the representation to counteract interference. It is therefore probable that at least one of the other two proposed processes must be invoked in addition to a removal process to produce a comprehensive account of maintenance in working memory.

Demonstrating that removal of information from working memory occurs thus does not disprove that other maintenance-enhancement processes do not also occur. But it certainly complicates detection and measurement of the use of any one process, because free time within a complex span trial may enhance memory via any of three plausible processes. If we accept that consolidation must occur immediately after encoding, then later free time prior to recall might reflect either refreshing of the current memoranda or removal of distractors or previous memoranda in the typical administration of a complex span task. Without building in any means to distinguish these processes, one cannot know which one may have occurred to improve recall. This

is unfortunately still the case for many studies purporting to explore maintenance processes in working memory: their characteristics are currently so similar that we cannot be sure which one(s) was(were) affected by the experimental manipulation. It is therefore increasingly important, as we move forward, that attempts to detect one of these processes at work acknowledge the other processes, and that researchers take care to limit their measurements in ways that allow isolation of the process under investigation. The studies we highlighted[6,12,19] show that this is possible, but the effort would be further assisted by clearer differentiation between processes that goes beyond their timing limitations. Refreshing and removal can occur during the same periods, and consolidation may also, if consolidation resumes after an interruption, one of the points that remains undecided[1]. Without further clarity on the characteristics of these processes, we fear that what is being measured in many experimental tests will remain ambiguous.

Consolidation, refreshing, and removal in models of working memory

The similarities between the processes—that they occur to generally enhance memory of both verbal and visual materials, that they require or at least benefit from undivided attention—situate them so that they must be assumed to rely on the general attentional components of working memory models. The time-based resource sharing (TBRS) model explicitly posits an executive loop that integrates disparate representations and strengthens these activations with periodic refreshing[4]. This differs from Baddeley's[32] vision of a central executive that processes information in that the TBRS model supposes that this central component both stores and attends to information, while the central executive of Baddeley's model does not include maintenance. (Baddeley and

Hitch[33] did include a central storage component but Baddeley later removed it from his model.) Similarly, the three processes must be assumed to engage the focus of attention in embedded process models of working memory[34,35], which temporarily activates a subset of the entire memory system. The convergence of approaches can be seen with recent studies of the focus of attention as a storage device by Baddeley, Hitch, and colleagues[36,37].

Integrating consolidation into working memory models is, we believe, the most challenging idea that arises from distinguishing between these maintenance processes. The notion of consolidation as a specific working memory process that requires attention and is distinguished from consolidation in long-term memory challenges the notion of passive (or peripheral) short-term storage as is widely presumed, and explicitly posited by the multi-component working memory model[32] and included alongside active maintenance in the most recent iteration of the TBRS[4] model. If novel information may be encoded and held in a passive short-term buffer without involvement of attention, it is unclear what role consolidation would play in maintaining or strengthening such representations. In the TBRS framework, which includes both passive short-term buffers and active maintenance, perhaps only memoranda that had been actively maintained would be eligible for consolidation. However, in the traditional multiple-component model, where no short-term storage necessarily involves attention, it is less clear how an attention-dependent consolidation process fits in. We know that passively holding information in mind for some period does not in and of itself strengthen a memory and render it more retrievable later[38]. If we are committed to incorporating the notion of consolidation into models of working memory, we must refine ideas about storage to accommodate it, or delineate circumstances under which

consolidation may not proceed, to avoid contradiction. What was once considered short-term storage may be considered to be sensory representation, "maintained" by its use in an ongoing procedure[39]. Assuming that fleeting representations are not consolidated, but persist via ongoing actions could be one way of preserving the idea that novel information may be briefly represented without undergoing the consolidation that would stabilize the representation. Moreover, though each process was presumed to require attention, their attentional demand may still differ: consolidation may be obligatory and may occur involuntarily, in contrast to refreshing and removal, which are assumed to occur voluntarily.

It is also possible that while carrying out one process, another is achieved as an added benefit. Cowan[40,41] proposed that the process of using attention to search through a list to determine which item to recall next in serial recall accomplishes a kind of refreshment of the memory, explaining why better recall does not have to mean faster recall and faster recall does not have to mean better recall[42]. Similarly, it is possible that refreshing accomplishes a sort of list-wide consolidation in which the stability of the representation has to do with the serial relation between items in the list[43].

The process of psychological theory building transcends borders, institutions, and laboratories, and is freely creative and unrestrained. Exercises like this one, in which many researchers join together to attempt to agree on definitions of the phenomena they study are vital because they allow us to see what, if any, common assumptions may constrain theory development. Identifying these crucial constraints is needed for consensus and progress with theory construction, so that over time we progress toward a more correct and complete vision. Without increasing constraint, we risk engaging in purely semantic exercises in which we talk about the same phenomena

using different words, arguing about nothing. This exercise in defining processes involved in working memory maintenance leaves us with more certain knowledge about what we believe, and also what we do not know, which is just as important in a young scientific field such as psychology. Three processes, consolidation, refreshing, and removal, apparently operate at different times with respect to the encoding of memoranda. In many other respects, these processes seem very similar. Knowing this affords us the opportunity to consider how else they may differ, so that we can continue considering whether and how these processes are unique, and whether they differ in how they fit with assumptions about the architecture of a working memory system. In our view, the current definitions of these processes are works in progress that, so far, only offer limited possibilities for comparing and further constraining models of working memory. We think it is nonetheless important to have explicitly stated definitions of these maintenance processes on the record. Another necessary future step will be to compare these processes with other widely-assumed maintenance-enhancement processes (e.g., verbal rehearsal, retrieval) that were not addressed explicitly in this exercise, but that may also serve to constrain how we believe maintenance occurs and how a model of working memory optimally describes maintenance. The precision we generate with these conversations clarifies which discussions transcend mere semantic disagreement, pointing out which controversies are most worthwhile to resolve.

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Competing interests

The authors have no competing interests to declare.

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