WHAT IS ATTENTIONAL REFRESHING IN WORKING MEMORY?

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Working memory is one of the most important topics of research in cognitive psychology. The cognitive revolution that introduced the computer metaphor to describe human cognitive functioning called for this system in charge of the temporary storage of incoming or retrieved information to permit its processing. In the past decades, one particular mechanism of maintenance, attentional refreshing, has attracted an increasing amount of interest in the field of working memory. However, this mechanism remains rather mysterious, and its functioning is conceived in very different ways across the literature. This article presents an up-to-date review on attentional refreshing through the joint effort of leading researchers in the domain. It highlights points of agreement and delineates future avenues of research.

Keywords: Refreshing; Attention; Working Memory; Maintenance; Long-Term Memory; Rehearsal

Working memory (WM) is in charge of maintaining information for short periods to facilitate its processing. Due to this dual function (maintenance and processing), WM is considered to be the hub of human cognition, [1] and it has become one of the most important topics of research in cognitive psychology, resulting in several models that account for its functioning. [2,3,4,5,6,7] To unveil WM functioning, one striking challenge is to understand how information is maintained in the face of temporal decay and distraction. Since the end of the 1990s, one particular mechanism of maintenance, attentional refreshing, has attracted an increasing amount of interest, to the point that the most famous model of WM, Baddeley's multi-component model, proposes it as the specific maintenance mechanism of the episodic buffer, and potentially for the visuospatial sketchpad as well. [2] However, this process remains rather mysterious, and both its conception and its operation are formulated in very different ways across the literature. Benefitting from the joint effort of leading researchers on this topic, the aim of this paper is to present an up-to-date review of the state of the research concerning attentional refreshing, synthesize different theoretical perspectives to uncover the potential consensus on some aspects, identify outstanding issues to resolve, and flesh out potential topics for future research.

How should attentional refreshing be defined?

Despite the many questions that remain to be clarified about attentional refreshing, there is at least some agreement on how to define it. Refreshing is broadly conceived as a domain-general maintenance mechanism that relies on attention to keep mental representations active. [3,8,9] This elementary process would increase the activation of recently presented, encoded, or retrieved information to keep it in an accessible state from moment-to-moment, thereby enabling real-time thinking. Refreshing involves boosting, prolonging, and strengthening the activation of these items when the capacity-limited focus of attention is directed to a representation in WM.[10] In other words, refreshing is the act of thinking of a representation that was activated just a moment earlier and has not yet become inactive. [11] It can also be conceived as an instance of reflective attention, that is, as an analogue of perceptual (e.g., visual) attention, where the 'spotlight' is placed on one out of potentially several active WM representations instead of one percept in the visual field. More generally, refreshing is an atomic component of a more global maintenance activity. For example, within a complex span paradigm in which participants have to maintain memory items while performing a concurrent task, several atomic refreshing episodes can take place when the participant is not engaged in any other attention-demanding activity (Figure 1). This would result in enhancing the activation level (both cognitively and neurally) of a representation that is currently active within WM, thereby preventing it from fading out of immediate awareness. Refreshing typically produces better immediate memory performance for refreshed information, relative to non-refreshed information or to tasks that preclude the ability to engage in attentional refreshing. Furthermore, some authors have proposed that refreshing causes the information to be better remembered in subsequent tests of episodic long-term memory. [12-14] It is also clear that attentional refreshing is distinct from another maintenance mechanism, articulatory rehearsal. Whereas rehearsal is exclusively dedicated to the maintenance of verbal information, refreshing can potentially maintain information of different sensory modalities, including verbal, visual, and spatial, as well as multimodal information. [15,16]

How does attentional refreshing operate?

In the literature, a first distinction in how refreshing is purported to function concerns its speed and its deliberateness. On the one hand, several authors (including proponents of the time-based resource-sharing, TBRS, model [3]) suppose that refreshing occurs quickly and likely largely outside of explicit awareness, or what could be colloquially referred to as “swift refreshing". On the other hand, others have studied a slower, more deliberate form of refreshing – e.g., turning one’s conscious attention to an item, thinking of it, or visualizing it for a time span on the order of several hundred milliseconds to seconds, perhaps in response to a cue in a laboratory task. [11,17]

An easy analogy can be made between the two forms of refreshing and different forms of perceptual attention: Shifts of perceptual attention may be deliberate, focused, and relatively long-lasting (on the order of one or more seconds) if a visual task relies on sustained attention to a specific item or location, but in the context of naturalistic, active vision, perceptual attention shifts can also be unpredictable, fleeting (several per second), and relatively implicit. And, for both perceptual attention and refreshing, the two forms are not entirely mutually exclusive; a person may sustain primary attentional focus on one percept or mental representation for one or more seconds, but also periodically make "swift" shifts of attention to other items. A significant challenge for future studies, and a promising avenue for new lines of research, would be to better elucidate the potential similarities and differences between these two forms of refreshing beyond the mere different time scales they may work on. Regardless, both forms of refreshing are seen as a distinct process from rehearsal. Rehearsal could be seen like juggling – catching and holding onto each item in turn, typically in a fairly fixed sequence, before heaving it aloft again, at which point it will rise and fall of its own accord for some time before needing to be re-caught. In contrast, refreshing is like spinning plates – in which the performer lightly touches each plate, sometimes in a fixed sequence but frequently not, and adds a small amount of energy in order to maintain it at a relatively steady level of activation.

Both forms of refreshing can be considered mechanisms for enhancing and prolonging the activation of WM representations, but the first form of refreshing ("swift refreshing") is more explicitly defined and conceptualized as a mechanism for WM maintenance. Cowan, [18] in his embedded-processes model, proposed that memory items are refreshed by bringing them back into the capacity-limited focus of attention, a proposal that was later endorsed by the first version of the TBRS model [19]. This continuous shifting of the focus of attention over the memory traces should increase their level of activation and keep them in a high state of accessibility. Other models have endorsed similar conceptions such as the TBRS* computational model of WM, [20] and recent studies have suggested that each atomic refreshing on a given memory trace may increase its specific level of activation. [8,9,21] Such refreshing can act as a sequential scanning or memory search in what Vergauwe and Cowan [22,23] called the central component of WM. In other words, a one-item focus of attention may enhance memory traces that are already in a high state of activation. For example, in the TBRS model, memory traces are temporarily stored in an episodic buffer. These mental representations that constitute the contents of WM are in a privileged state of accessibility that is assumed to decrease over time (due to time-based decay), thereby leading to forgetting. Refocusing on an item allows the memory trace to be boosted, preventing its forgetting. By sequentially browsing the contents of the episodic buffer, the focus of attention serially reactivates the contents of WM, allowing task-relevant information to remain active and available indefinitely.

Both forms of refreshing could also be compatible with Oberauer's concentric model, [25] in which three states of representation accessibility are described. In this model, the outermost state, the activated part of long-term memory holds representations that may become relevant for the ongoing task (e.g., letters when performing a letter span task); within those representations, the region of direct access keeps a limited number of relevant items easily accessible, while binding them to their relevant context (e.g., the sequence of letters seen in the current trial); and finally, in the innermost state, the focus of attention is responsible for selecting a single item for manipulation, bringing it into a heightened state of accessibility. Refreshing in this model is implemented by the operation of the focus of attention upon the contents available in the region of direct access.

On which kind of representations does refreshing operate?

A remaining debate concerns what exactly is being reactivated by refreshing. Some authors favor the view that refreshing increases the links of a memory trace with its serial position within the list and with the adjacent items in the list. [8,9,20,21] The idea that the main role of refreshing is to strengthen the binding of an item to its serial position in a trial or more generally to its original context (e.g., its spatial location in an array) is often foregrounded by some authors. [25,26] This strengthening of the content-context bindings, which increases the memory for "what" was "where", would make representations more available for retrieval from WM and also episodic LTM. [27]

This debate could result from differences regarding what the authors consider to be a WM representation. This could consist of the binding between a content (e.g., a color or a letter) and a context (e.g., spatial location or serial order), and accessing it could depend on cue-based retrieval (Figure 2c). [28] In such a theoretical view, refreshing likely involves the selection of a single item into the focus of attention for binding strengthening. [28,29] Refreshing does not simply boost item-level information (e.g., increasing the likelihood that one will remember having seen a red object), but it actually promotes memory about item-context associations (e.g., memory of a red apple, or memory of red in a given location).

Alternatively, one of the main functions of WM could be the construction of mental representations by the concatenation of perceptual information provided by the environment and atomic elements stored in LTM because no representation pre-exists in LTM. Forgetting would then result in a degradation of this construction, and refreshing would aim at preserving or reconstructing the mental representations to be as close as possible to their original form. [3] Similarly, Johnson [11,17] views the fundamental unit upon which refreshing operates to be the "representation," which is a concept whose common-usage meaning is nearly as intuitive and natural as that of an "object" in the study of vision, and equally difficult to define in explicit and concrete terms. Like visual objects, mental representations can be complex and multifaceted, and can consist of smaller parts that are themselves objects/representations, respectively. For example, a mental representation of one's dog may comprise sub-representations with visual, emotional, verbal/semantic, etc., components of the overall representation, and it may be possible to specifically refresh (i.e., reflectively attend to) one of these aspects of the overall representation, just as it is possible to direct visual attention to either an entire object (say, a car) or one of its sub-objects (e.g., one of its tires). Thus, the question of what exactly is being reactivated depends primarily on what one considers a WM or mental "representation" and also on how the relationships between WM and LTM are construed.

How is refreshing of memory traces implemented?

Another challenge consists of understanding how refreshing is implemented. Despite differences in the exact functioning proposed for refreshing, it is often seen as a serial mechanism that proceeds at the item level over the representations available in the region of direct access [26] or episodic buffer, [16] resulting in a strengthening of the memory traces of the corresponding modality (i.e., visual-spatial, verbal).

Recent studies have tested the serial refreshing hypothesis according to which spontaneous refreshing of a memory list operates serially, with the focus of attention cycling from one item to the next. [16,23,30-34] An obvious way of implementing serial refreshing consists of refreshing the items of a memory list in a cumulative, forward order, i.e., in the order of presentation starting with the first-presented memory item, followed by the second-presented memory item, etc. Regardless of the way in which serial refreshing is implemented, the idea is that items are brought into the focus of attention, one after the other (Figure 1a). Consequently, the maintenance of order (e.g., the order of words in a memory list) could be a by-product of the cumulative and sequential nature of refreshing. [35]

Alternative implementations have also been proposed. Although it is commonly admitted that refreshing cannot take place at the same time as other attentionally demanding processes because of an attentional bottleneck (as initially proposed by Barrouillet and colleagues, [19] Figure 1a), atomic refreshing episodes can be implemented in ways that are not cumulative. One alternative refreshing schedule could involve refreshing the one item that is the most likely to be lost, or that is the least activated, at any given time (Figure 1b). Yet another alternative proposal comes from the idea that refreshing may be neither cumulative nor serial: the focus of attention may be able to zoom in on a single item or zoom out to span multiple items as a function of the constraints of the task. Indeed, in the TBRS* architecture, [38] the implementation of such a schedule in which several items are simultaneously refreshed within a larger attentional focus [8,9] (Figure 1c) was able to fit published behavioral data [36,37] and reproduced the major TBRS predictions through a fictional set of experiments that were proposed by Oberauer and Lewandowsky. [38]

It remains possible that these different schedules reflect the distinction between fast and slower refreshing. Whereas the slower and more deliberate form of refreshing can be easily conceived as a serial process, the swift refreshing mode, in its faster, more implicit "scanning" form, may involve the deployment of reflective attention in parallel across multiple representations concurrently. On the other hand, it may well be that the more rapid form of refreshing is still a serial process, but that the alternations in attentional focus between items occur so quickly that the process would appear to be parallel to all but the most fine-grained measurements; indeed, at sufficiently high scanning rates, acts of refreshing may occur so quickly and briefly that a clear distinction between serial and parallel processing cannot be made with conventional psychological methodologies.

Regardless of the way in which refreshing is implemented, the item that is represented in the focus of attention is assumed to be in a privileged state of heightened accessibility. [29,39,40] The local effect of refreshing is thus the heightened accessibility of the just-refreshed WM representation. [32] The spontaneous refreshing reactivates these representations without modifying the nature of the involved representations. However, it is possible that mere reactivation through refreshing can be followed by other attentional processes that might modify and/or enrich the involved WM representations, potentially also linking together some or all representations that are activated above threshold at a given point in time.

Which type of attention is engaged?

Most researchers assume that the type of attention engaged in refreshing is controlled or executive, domain-general, central, and internal in nature, as opposed to domain-specific, perceptual, and external forms of attention.[5] The former is the attention needed to access stimuli and goal representations as well as to resolve conflicts between activated thoughts or action plans. Any cognitive task that taxes this type of attention during the retention interval of a WM task will limit the opportunity to refresh memory items, thus resulting in poorer immediate memory performance.[19,36,41] The implication of attention distinguishes refreshing and rehearsal because rehearsal would barely rely on attention, except when required at the onset of the motor plan.

An alternative is to consider refreshing as highly analogous to the role that perceptual attention plays in enhancing the level of activation of sensory inputs. In Johnson's view, the process of refreshing does not require the engagement of a particular form of attention, per se – rather, the refresh operation *is* a kind of attention. [11,17] This form of attention is presumed to overlap substantially with perceptual attention, both in terms of its cognitive effects and its neural implementation. Like perceptual attention, reflective attention (i.e., refreshing) is thought to work in generally the same manner regardless of which type of material is refreshed, although the specific implementation details may differ in small ways (e.g., in the particular neural sub-regions involved in refreshing different types of material). And like perceptual attention, short of eliminating consciousness, it is likely not possible to block refreshing entirely; as long as sensory stimuli are present, perceptual attention will be deployed in some form among them, and similarly, as long as there are thoughts in mind, reflective attention will be deployed among those. In fact, in the MEM framework, [11] refreshing is a critical aspect of the stream of consciousness, with that stream essentially being defined by which representations are reflectively attended from moment to moment. That said, reflective attention can be inhibited or diminished in various ways. For example, there is at least a partial trade-off between externally-directed and internally-directed attention; when one's central attentional resources are more strongly directed externally (toward the perceptual world), there tends to be a concomitant decline in reflective attention, and vice versa. [42]

This trade-off between internal and perceptual attention has been empirically tested in a visual WM task (Figure 2a) by assessing the costs of distractor tasks engaging either visual attention (monitor changes in brightness on a visually displayed stimulus) or central attention (decide whether a tone was of a high or low pitch). In that study, only the central-attention distractor task impaired visual WM, [43] suggesting that refreshing depends on central attention, and may operate in a parallel and non-interfering manner with perceptual attention tasks that do not draw upon central resources. It remains unclear if the involvement of central attention is the sole factor distinguishing when refreshing and perceptual attention do and do not interfere with each other; other factors, such as difficulty or load, have also been suggested. [42] However, one possibility is that tasks with high perceptual attention loads may in turn place greater demands on central attention, which could explain the existence of interference in those cases.

It should be noted that poor immediate performance in dual-task conditions might also result from blocking other attentional processes that contribute to performance (e.g., consolidation). It is currently an open question whether the attentional requirements differ for different kinds of memory materials; it is possible that the attentional demands are higher for more complex materials (e.g., with slower refreshing rates for more complex materials) or less familiar items. Indeed, some studies have claimed that certain types of unfamiliar or non-categorical information such as non-Latin characters [44] or fonts [16] may not be refreshed because a mental representation cannot be constructed in WM. In other words, not all forms of information would give rise to a mental representation; some may be solely maintained in a sensory format, in which they can not be manipulated, transformed or refreshed. Our theoretical perspective on refreshing does not critically hinge on claims of what can and cannot be represented in WM, which we view as a problem for the broader cognitive psychology community. However, obtaining better support for our general claim that refreshing operates on all forms of information that can be expressed as mental representations remains an outstanding issue for future research.

What is the time course of refreshing?

With regard to the time course of the spontaneous, scanning-style refreshing of a set of elements, it has been proposed that the focus of attention would rotate quickly among the different to-be-refreshed WM representations (i.e., high-speed refreshing) at a rate of 40-50 ms per item in young adults. [3,16, 22, 23] Computational modeling [45] suggests that this rate could be longer in older adults (ca. 200 ms) than in young adults (ca. 80 ms). Given that there is an attentional bottleneck when a distractor task has to be carried out concurrently with WM maintenance, one of two things can happen. Either the cycling through the contents of WM is interrupted because the task requires central-internal attention (particularly if processing this information is considered important and urgent), or processing of the distractor task is postponed until the refreshing cycle is completed, which is likely the case when there is little or no time pressure, or when the memory task is given higher priority.

Other studies have examined the time course of slower and more deliberate instances of refreshing. Evidence from EEG experiments suggests that this more deliberate refresh process comprises at least two temporal sub-components, one peaking approximately 400 ms following a cue to refresh a representation, and another, more sustained component lasting from approximately 800–1400 ms post-cue. [46] In conjunction with evidence from other EEG and fMRI studies, the earlier sub-component was regarded as being associated with anterior prefrontal cortex activity and the initiation of the refresh action based on interpreting the cue presented, and the later component as being associated with an increase in neural activity in posterior brain regions that actually encode the information comprising a mental representation (e.g., visual regions, in the case of mental representations of visual stimuli).

The study of deliberate acts of refreshing has been accomplished mainly through the cueing of representations during the retention interval of a WM task (with so-called retro-cues). Retro-cueing benefits can emerge for time intervals as short as 150-250 ms. [47,48] This is likely an overestimation of the time required to (deliberately) refresh an item though, because this estimate also comprises the time to detect and interpret the cue. Future studies may compare cueing conditions with and without refreshing demands, while varying the time to use the cue, in an effort to estimate pure instructed refreshing speed. This may or may not converge with the time it takes to spontaneously refresh items, which has been suggested to be as fast as 50 ms per item. How to measure spontaneous refreshing speed is still an open question, though. Furthermore, as mentioned previously, it is not clear whether refreshing can be interrupted or if it proceeds in a ballistic fashion after it is started, thereby postponing other attentionally-demanding activities or even preventing them, in a manner similar to an attentional blink. [49] Again retro-cues could become an important tool here: by varying the time between two successive retro-cues, one may study whether a second instruction to refresh stops the refreshing of a first cued item, or conversely whether an ongoing first instance of refreshing inhibits the initiation of a second.

What limits attentional refreshing?

The effectiveness of refreshing depends on several factors that can be split into two main categories: the constraints imposed by the task and individual differences. Regarding the former, because refreshing requires domain-general central attention, which is a limited resource, its efficiency is limited by any increase in concurrent central attentional demand (e.g., the cognitive load of a secondary task in complex span tasks). Such an increase can result from various manipulations, such as increasing the pace of the to-be-processed distractors or the type of processing to be performed on the distractors. [50] The impact of these manipulations on recall performance indexes the use of an attentional maintenance mechanism, which is clearly distinct from the articulatory rehearsal that barely needs attention. The temporal regularity of the task, which improves the allocation of attentional resources according to the Dynamic Attending Theory, [51] seems to modulate refreshing efficiency in complex span tasks. For example, WM performance can be enhanced in the presence of an isochronous rhythm during the retention interval.[52]

Concerning individual differences, there is some evidence that refreshing efficiency changes over the lifespan, such that it is relatively impaired in older adults [13, 46,52-56] and children [57-59] compared to young adults. Moreover, children younger than the age of 7 do not seem to spontaneously use refreshing, as they are not sensitive to the variation in concurrent attentional demand that reliably affects performance in young adults and older children.

Besides these two main factors, other factors such as prior knowledge, expertise, or motivation may also influence refreshing efficiency. In particular, the nature of the to-be-maintained items may influence the use of refreshing. Recent research indicates that some types of memoranda, for example, letter fonts [16] and unusual symbols [44] are not sensitive to manipulations of the cognitive load in a distractor task. One common characteristic amongst these features is that they seem less categorical and less grounded in long-term memory than refreshable features (e.g., letters, words, locations in matrices). This suggests that LTM may play a role in the function of refreshing, a point discussed in the following section. This may apply however, only for spontaneous, fast refreshing modes. When participants are cued to (deliberately) refresh continuous visual features (colors or orientations, as shown in Figure 2a) in WM, their performance improves as a direct function of the number of refreshing opportunities. [10,43] These studies demonstrate that continuous visual features can be attended to in WM, thereby receiving a focusing boost. Hence, in principle, they are "refreshable". It remains possible that more implicit forms of refreshing do not occur spontaneously for these types of materials.

Does refreshing rely on long-term memory?

Currently, several models describe the relationships between LTM and WM, either as two separable systems of memory, [2,3,60] or as a unitary memory system. [61] Between these two extreme theoretical positions, several intermediate theories propose WM as a subset of LTM representations that are temporarily in a qualitatively distinct state of accessibility. [25,39] Despite the fundamental difference regarding the extent to which LTM and WM are related to each other, most theoretical conceptions highlight the necessity of a two-way information channel between the two systems. Attentional refreshing could be a central process involved in this information channel.

In the view of the MEM framework, [13,17] all processes are fundamentally integrated with LTM; in other words, LTM is not considered a separate system so much as a fundamental part of the machinery of all cognitive processing. All past cognition leaves traces (in the form of altered neural pathways), and these traces necessarily must shape all future cognition. That said, refreshing can certainly operate upon a WM representation that was recently created as a result of a new sensory/perceptual experience of a stimulus that had not previously existed in an individual's LTM; still, even basic perceptual processing relies on prior experience in order to derive meaningful interpretations of the current sensory input, and thus perception itself is fundamentally reliant on LTM knowledge.

As discussed in the previous section, the extant research regarding the reliance of refreshing on LTM is somewhat mixed. In tasks involving WM maintenance and the more rapid ("swift") form of refreshing, performance for novel visual stimuli was found to decrease over the course of an unfilled delay and their maintenance was not sensitive to the attentional load of concurrent distractor tasks. [16,44]. This seems to suggest that either this form of refreshing cannot operate on this type of information or participants do not spontaneously do so. At the moment, we lack evidence to distinguish between these two hypotheses. One possible avenue forward is to examine the “refreshable” nature of a representation by the size of the benefits observed when these representations are explicitly cued to be refreshed (using retro-cues as discussed above). Neuroimaging studies involving the slower, more deliberate form of refreshing for novel faces and scenes suggest that participants are able to recover at least part of the visual information presented, though it was substantially less than the information (as indexed by activation in visual brain regions) associated with visual re-presentation of the items. [62,63]

The recent version of the TBRS model [3] suggests that refreshing shares some similarity with the redintegration mechanism as proposed by Hulme and colleagues [64] . They assume redintegration occurs at recall by using knowledge stored in LTM to repair degraded WM traces. When attention is available, these traces can be repaired by using LTM elements. The difference between the original proposal [64] and the TBRS latter conception [3] is that refreshing by redintegration could occur during the maintenance period (i.e., between encoding and recall) and not only at recall. This conception [3] leads to some predictions about WM functioning and its interactions with LTM. If refreshing relies on the retrieval of LTM knowledge, one can expect that the efficiency of refreshing should be impacted by the ease to retrieve such knowledge. For example, high-frequency words are quickly retrieved from LTM, and thus their redintegration should be easier than low-frequency words. Some unpublished recent work seems to contradict this prediction, because no difference in refreshing efficiency was observed while manipulating factors known for affecting LTM retrieval, like word frequency, lexicality, or semantic relatedness between memory items. These latest findings call for alternative functioning for attentional refreshing.

An alternative viewpoint is that the effectiveness of refreshing should not necessarily depend on whether the refreshed information represents existing knowledge in LTM. Instead, it may be the case that LTM bolsters the quality of the representations in WM overall relative to novel information, but the actual process of refreshing should be independent of LTM. A limited number of items are centrally represented in WM and these items are sequentially brought into the focus of attention during spontaneous refreshing of a set of elements. In this viewpoint, refreshing interacts directly only with representations that are active in WM and no critical role is assigned to LTM, although it remains possible that some grounding in LTM is necessary to construct a refreshable WM representation.

What counts as evidence for the existence of refreshing?

As mentioned previously, two different forms of refreshing can be defined according to their speed (slow vs. fast) and whether they are performed implicitly or explicitly. Depending on the definition one accepts for the process of refreshing, its existence might be self-evident. For example, it is clear that people are capable of focusing their internal, or reflective, attention towards certain representations in WM and not others, so if one choose this as the definition of refreshing (as is the case for the MEM framework), then the process must necessarily exist. This assertion is strengthened by a great deal of evidence that the slower, more deliberate form of refreshing has meaningful cognitive and neural correlates, which speaks to the utility of this construct as a component of cognitive psychological models. Furthermore, many of these effects have clear parallels in the somewhat more thoroughly understood domain of perceptual attention, which specifically highlights the usefulness of construing the refreshing process as a form of reflective attention. These effects include the fact that refreshing enhances LTM, is specifically impaired in aging whereas other cognitive processes (e.g., rehearsal) are relatively preserved, can produce temporary impairments in accessing representations similar to the perceptual phenomenon of inhibition-of-return, [63] and exhibits a characteristic pattern of neural activation that partially overlaps with activity patterns associated with perceptual attention. [62,63,65] In such a view, the existence of some process akin to a form of refreshing is virtually indisputable; the main (or perhaps only) way in which this view could be weakened is if an alternative model were proposed that could better (and/or more succinctly) account for the extant experimental evidence.

In parallel to this conception of refreshing, others favor an alternative view in which refreshing is a faster and more implicit process that nevertheless also relies on controlled or executive attention. It is important to say that there is no reason the two accounts of refreshing could not coexist. They could simply be interpreted as two aspects of what is fundamentally the same process, just with different degrees of intentionality and different time scales. The evidence for the "fast" refreshing has largely come from paradigms that vary the ability or instruction to engage in refreshing, either by varying cognitive load or explicitly directing participants to refresh memoranda. [3,10,36,66] The cognitive load of a task is estimated by the proportion of time during which attention is captured by a secondary activity and distracted from maintenance over the total time during which items have to be maintained. In several studies, it has been shown that increasing the cognitive load results in a linear decrease of the number of recalled items (Figure 3). Importantly, parallel evidence comes from verbal and visuospatial domains, suggesting that refreshing is a domain-general function. [41]

In contrast, characterizations of the deliberate, slower forms of refreshing have largely arisen from explicitly guiding the focus of attention to individual WM elements via retro-cues. [62,63] Numerous studies have shown that valid retro-cues improve performance for tests of the cued item. This retro-cue benefit can, however, be explained without recourse to refreshing, with one competitive view being that non-cued items are deemed irrelevant by the reliable cue, being therefore removed from WM to reduce inter-item interference. [48] To measure the contribution of refreshing irrespective of removal, multiple cues have been used in a visual WM task: participants maintained an array of colors, and during the retention interval a sequence of four cues marked individual items to be refreshed 0, 1, or 2 times (Figure 2a).[10] To minimize the incentive to remove non-cued items, the cues were not informative regarding the to-be-tested item. The error in reporting the test color decreased the more often an item was refreshed (Figure 2b), showing that each refreshing step conferred a boost to the accessibility of the attended WM representation. This evidence generally indicates that refreshing improves retrieval from WM. In addition, neuroimaging evidence suggests that enhancement of the refreshed item and suppression of a non-refreshed item both occur in response to a retro-cue, and thus both excitatory and inhibitory effects of refreshing may contribute to the overall behavioral advantage for refreshed versus non-refreshed information in WM and LTM. [11]

It should be noted that in previous work,[14,26,67,68] it has been suggested that a further source of evidence for refreshing is the McCabe effect: the finding that retrieval from episodic LTM is enhanced for memoranda whose maintenance is regularly interrupted by a secondary task (i.e., complex span) compared to memoranda presented without a secondary task (i.e., simple span). [34] Participants presumably covertly retrieve the previously presented memoranda during pauses between the secondary task and the next memorandum during complex span tasks, and this observation may lead one to hypothesize that refreshing and covert retrieval might be the same process. Indeed, McCabe proposed refreshing as a potential mechanism for covert retrieval. However, McCabe's initial covert retrieval model is somewhat agnostic as to its specific mechanism and partially conflates the concepts of refreshing, retrieval, rehearsal, and additional operations. The following discussion will use terminology consistent with our usage elsewhere in this paper.

In contrast to our characterization of swift refreshing as a cycling of very recently presented and still active representations in the focus of attention, covert retrieval may instead reflect retrieval from outside the central component of WM (Figure 4). In this view, refreshing operates on active information within the central component of WM, bringing active representations one-by-one into the focus of attention, whereas covert retrieval recovers information from outside of the central component of WM (i.e., LTM). Accordingly, refreshing and covert retrieval would be theoretically distinguishable. The investigations of this interpretation of covert retrieval are still underway, but results thus far indicate it may be accurate. If refreshing and covert retrieval are indistinct, then varying the attentional demand of the secondary processing component should likewise moderate the McCabe effect as it does for immediate recall from WM (Figure 3). In several thus far unpublished studies and one published study [69] , this was not the case. Furthermore, a recent study has revealed that the McCabe effect may be an instance of the benefit incurred by prolonging the time individual items can be attended to just after they have been encoded, with no real benefit of interspersing distraction episodes during the maintenance of these items. [70] Given this accruing evidence, it is less likely that refreshing and covert retrieval are identical, and instead it is proposed that retrieval of information from outside of the central component of WM may co-occur alongside the swift refreshing that takes place within the central component. Furthermore, this understanding of refreshing and retrieval may facilitate the resolution of incongruous findings, such as whether refreshing relies on LTM. [68]

Finally, another source of evidence is the age-related changes in refreshing throughout childhood. Contrary to older children, recall performance in children younger than 7 years of age is not sensitive to variation in cognitive load but to the overall maintenance duration of the secondary activity during a complex span task. [71] This suggests that preschoolers are not using attentional refreshing to maintain information, which suffers from a time-related decay. After 7, children's performance is affected by the cognitive load of the secondary task, with the impact of cognitive load increased with age. [54] Refreshing thus seems increasingly efficient in maintaining memory traces with age, and this efficiency is related to age-related changes in processing speed. [72] However, aging studies enlighten the fact that maintaining WM traces is probably more complex than a simple recirculation of the information into the focus of attention. [54] Indeed, people report using strategies (e.g., elaboration) to maintain information during a complex span task. [53,73] Hence, it remains to be understood to what extent alternative maintenance mechanisms or strategies can account for the observed age-related variation in recall performance as a function of cognitive load.

To summarize, clear evidence for refreshing consists of demonstrating the distant effect of refreshing, i.e., refreshing results in better immediate and delayed memory performance, and the local effect of refreshing, i.e., the increased activation and accessibility of just-refreshed information. Both of these should be done while excluding the operation of other maintenance mechanisms (like subvocal rehearsal) and could be compared between situations in which the act of refreshing occurs spontaneously vs. upon instructions.

Conclusion

Certainly, there are challenges in characterizing how refreshing functions and even in establishing definitively whether such a process exists. The dispute over the existence of refreshing largely may have originated from an unnecessary conflation of refreshing with decay-based forgetting. If one ascribes the role of protection from trace decay in WM to refreshing, and yet trace decay may not exist, then it is reasonable to argue that refreshing is a superfluous function. However, if refreshing is instead conceptualized as a mechanism that strengthens representations as it was originally conceived, then the link between refreshing and decay is not necessary.

Further details of how refreshing functions remain to be fully clarified. A challenge for the notion that refreshing acts serially and cumulatively, with each item refreshed one-by-one in its original order of presentation, is the failure to find a change in the accessibility of the presumably refreshed letters during a probe-span task. Instead, it may be the case that refreshing acts by strengthening the least-activated item first. Furthermore, the precise time course of refreshing, whether refreshing strengthens content-context bindings or only the items themselves, and whether LTM moderates the efficiency of refreshing are all outstanding issues to clarify.

Nevertheless, the significant progress that has been made should not be understated. The current status of the field has moved forward to such an extent that researchers from different theoretical perspectives are working together largely to refine the details of how refreshing functions to direct attention in WM to representations that are no longer physically present in the environment. This article integrating these perspectives from different authors is in itself a strong sign of the change the field is experiencing.

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Figure Captions

Figure 1 : This diagram illustrates the evolution of the item/position activation values in the TBRS* model in a fictional task in which there are six to-be-recalled letters (ABCDEF) and two distractors interleaved after each letter for which a location judgment task has to be performed. The first item to be maintained is A. The light gray area represents the encoding step during which the activation of A is increased. The next white area represents the time devoted to refreshing items. Since there is only one item (A) encoded so far in WM, the activation value continues to increase until a distracting episode occurs (horizontal hatching area); activation then decays. The task then alternates between free time (refreshing) and distractors (decay) until a new item, B, occurs. During the free time following the encoding of B, as well as during the free time following a concurrent processing episode, the two items (A and B) are refreshed in turn: when one is refreshed, the other one decays, and so on until the end of the series. This evolution of activations values derives from the default cumulative schedule of refreshing implemented by Oberauer and Lewandowsky[20]. The magnifying circle at the right side of the diagram emphasizes the time course of the respective activation of the six items during a refreshing phase as a function of the three schedules: (a) cumulative, (b) least activated first and (c) expanded focus of attention[8].

Figure 2. Panel A: flow of events in the refreshing visual WM task employed by Souza et al. [11]. Participants encoded six colored dots, and at the end of a brief interval were asked to reproduce the color of one dot (marked by a white circle) using a color wheel. During maintenance, cues (arrow) instructed participants to think of WM items (refreshing instruction). WM items were cued 0, 1, or 2 times (see inset). Panel B: error (distance in degrees on the color wheel) in reproducing the test item's color as a function of the number of refreshing steps this item received in the four experiments reported by Souza et al.[11]. Panel C: schematic illustration of the effect of refreshing on

the bindings between content (represented here by color) and the context (spatial location on the screen).

Figure 3: Mean WM spans as a function of the approximate cognitive load induced by a variety of tasks involving different executive functions such as response selection and retrieval[49], updating and inhibition[36].

Figure 4: Two alternative accounts for the functioning of the covert retrieval mechanism. M = memory item; in this example, participants would be attempting to remember a four-item list. On the left, all four items are currently available in the central component of WM, and refreshing them in sequence maintains them as active and available. On the right, prior to covert retrieval, no task-relevant information is within the central component of WM, and the list must be “reloaded” from longer-term memory stores.