Note the mechanism of action and internal process of refresh.

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Abstract

Attentional refreshing is a working memory maintenance mechanism independent of articulatory rehearsal. It promotes, prolongs, and strengthens the activation of information by retrieving it from working memory into the focus of attention. When articulatory rehearsal is constrained, attentional refreshing helps people maintain memory. A common strategy for attentional refreshing is to prioritize weakly activated items, though experience-related stimuli may also receive prioritized refreshing. Future research could further investigate the mechanisms and internal processes of attentional refreshing by examining whether it can act upon memory precision, how interference or processing tasks affect refreshing speed, and whether prioritizing weakly activated items remains a viable strategy under high attentional load conditions.

Full Text

The Mechanism and Internal Processing of Attentional Refreshing

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Abstract: Attentional refreshing is a working memory maintenance mechanism independent of articulatory rehearsal. It boosts, prolongs, and strengthens the activation of information in working memory by retrieving this information into the focus of attention. Attentional refreshing helps people maintain memory when rehearsal is limited. The common strategy of attentional refreshing is to prioritize weakly activated items, though sometimes experience-related stimuli also receive priority. Future research could further explore the mechanism and internal processing of attentional refreshing by investigating whether attentional refreshing can affect memory precision, how interference or processing tasks impact refreshing speed, and whether prioritizing weakly activated items remains a reasonable strategy under high attentional load conditions.

Keywords: attentional refreshing, working memory, internal attention

1 Introduction

Working memory serves as a cognitive hub by connecting memory maintenance and processing systems. Forgetting and maintenance of information constitute a central focus of working memory research. Most current theories posit that information in working memory decays naturally over time (Barrouillet & Camos, 2012a; Ricker et al., 2020), while an attention-dependent maintenance mechanism can resist this forgetting—this mechanism is known as attentional refreshing.

The concept of refreshing initially emerged in Johnson' s (1992) Multiple-Entry, Modular Memory System framework. In this framework, refreshing is a simple reflexive process that extends the activation duration of recently activated representations. Subsequently, Barrouillet and Camos (2012b) linked refreshing with attention and memory retrieval in their Time-Based Resource-Sharing (TBRS) model. Attentional refreshing reactivates decaying memory traces by retrieving information into the focus of attention. This mechanism of attentional refreshing has been widely accepted by researchers and has provided new directions for many working memory studies. Research on attentional refreshing can help clarify how contents in working memory decay and are maintained. Additionally, the attentional demands of the refreshing process contribute to our understanding of the relationship between maintenance and processing in working memory.

Although recent research has greatly deepened our understanding of attentional refreshing, its mechanisms and internal processes remain controversial and enigmatic because attentional refreshing is an internal attentional process that is difficult to observe directly. Therefore, this article focuses on the mechanisms and internal processes of attentional refreshing, aiming to provide a comprehensive explanation of how attentional refreshing operates based on existing research.

2 Attentional Refreshing and Evidence for Its Independence from Articulatory Rehearsal

Attentional refreshing and articulatory rehearsal are the two primary maintenance mechanisms in working memory. Attentional refreshing promotes and extends the activation of information by retrieving it into the focus of attention (Camos et al., 2018). Depending on how it is implemented, attentional refreshing can be divided into two forms. One is spontaneous attentional refreshing, which is typically unconscious and rapid. In this form, individuals refresh a single item in approximately 50 ms (Vergauwe et al., 2014). The other is externally cued attentional refreshing, which is typically conscious and slow. This form of attentional refreshing usually requires cues to guide participants to refresh specific items (van Moorselaar et al., 2015). Articulatory rehearsal, by contrast, is an articulatory process primarily used to maintain phonologically represented information in working memory (Oberauer, 2019).

Existing evidence indicates that attentional refreshing and articulatory rehearsal are relatively independent processes. Attentional refreshing depends on available attentional resources, whereas articulatory rehearsal depends on the articulatory system. They can act separately on working memory maintenance processes and activate different brain regions (Camos et al., 2009; Raye et al., 2007; Trost & Gruber, 2012). To examine the effectiveness of attentional refreshing and articulatory suppression on memory, Camos et al. (2009) designed two articulatory suppression conditions in Experiment 1 and manipulated whether participants could perform attentional refreshing. In one condition, participants had to read aloud and solve simple arithmetic problems presented on the screen (e.g., $3 + 5 = ?$) during the memory maintenance period. Since the calculation occupied participants' attentional resources, they could not perform attentional refreshing in this condition. In another condition, participants only needed to read aloud arithmetic equations presented on the screen (e.g., $3 + 5 = 8$) while maintaining memory. Since participants did not need to calculate, they could perform attentional refreshing while completing the task. Results showed that when articulatory rehearsal was completely suppressed, participants had better recall performance in the condition where they could perform attentional refreshing compared to when they could not. Correspondingly, in Experiment 2, they manipulated whether participants could perform articulatory rehearsal under two attentional refreshing suppression conditions. Results showed that when attentional refreshing was completely blocked, participants had better recall performance in the condition where they could perform articulatory rehearsal compared to when they could not. These two experiments demonstrate that attentional refreshing and articulatory rehearsal can independently help individuals maintain memory when the other process is blocked. Additionally, Raye et al. (2007) found that participants' articulatory rehearsal of phonological information activated the ventrolateral prefrontal cortex, whereas attentional refreshing of information activated the dorsolateral prefrontal cortex. Furthermore, Trost and Gruber (2012) studied brain-damaged patients and found that patients with Broca' s area damage had difficulty maintaining memory through articulatory rehearsal, but their attentional refreshing function remained intact. Conversely, patients with bilateral frontal pole damage showed impaired attentional refreshing function, but their articulatory rehearsal performance was unaffected.

3 Research Paradigms for Attentional Refreshing

Previous research on attentional refreshing has primarily used the retro-cue paradigm and complex span tasks. The retro-cue paradigm typically guides participants to refresh specific items through a cue after they have encoded the memory material (Bartsch et al., 2018). This paradigm measures passive, guided attentional refreshing. Complex span tasks hinder participants' ability to refresh by inserting attention-demanding interference tasks during the maintenance period, thereby measuring spontaneous attentional refreshing (Camos et al., 2017; Abadie & Camos, 2018). However, neither paradigm can measure the internal processes of attentional refreshing. A recently developed paradigm using eye-tracking equipment—the blank screen paradigm (Káldi & Babarczy, 2021)—provides new possibilities for studying attentional refreshing. This paradigm describes the internal processes of attentional refreshing by analyzing participants' eye movement patterns on a blank screen during the memory maintenance period. However, the mechanism of this paradigm still has some 疑点 and requires further examination.

3.1 Retro-Cue Paradigm

A commonly used paradigm in attentional refreshing research is the retro-cue paradigm. Since participants need to process the retro-cue and refresh under its guidance, this paradigm studies slow, passive attentional refreshing processes. This paradigm was first used in research by Griffin and Nobre (2003). In the experiment, participants first needed to memorize multiple stimuli presented at different locations on the screen. After the stimuli disappeared, a spatial cue appeared at the center of the screen, pointing to the location of one stimulus. This cue guided participants to direct their attention to the internal representation of the stimulus at that location, thereby reactivating the representation. Participants then needed to judge whether a probe stimulus presented at the center of the screen was one of the previously presented stimuli. Results showed that valid retro-cues shortened response times for judgments compared to neutral cues with no specific direction. This form of retro-cue is called an endogenous cue, which is presented at the center of the screen and points to stimulus locations. Subsequent research further demonstrated that exogenous cues (cues presented at stimulus locations) and feature cues (cues presented at the center of the screen indicating stimulus features, such as a red figure presented at the center guiding participants to focus attention on previously presented red stimuli) can also guide participants to perform attentional refreshing (Heuer & Schubö, 2016; Vandenbroucke et al., 2014). The retro-cue paradigm is direct and convenient, allowing manipulation of the target and frequency of attentional refreshing, but it cannot be used to study spontaneous attentional refreshing processes.

3.2 Complex Span Task

Complex span tasks were originally developed to assess working memory capacity (Daneman & Carpenter, 1980). In these tasks, participants must complete additional processing tasks while memorizing information. For example, participants read a series of sentences and judged whether they made sense while simultaneously memorizing the final word of each sentence. In attentional refreshing research, processing tasks typically involve arithmetic tasks (e.g., 3 + 5 = ?) or spatial tasks (e.g., judging whether a presented stimulus is at the top or bottom of the screen). Compared to pure memory tasks, the additional processing tasks occupy participants' attentional resources, preventing them from refreshing memory items and thereby reducing recall performance. Complex span tasks can reflect the role of spontaneous refreshing in working memory maintenance, enabling researchers to explore how different types of materials (e.g., familiarity) affect attentional refreshing. However, memory is inevitably influenced by encoding and consolidation processes in addition to attentional refreshing, making it difficult for complex span tasks to measure the unique contribution of attentional refreshing to memory.

3.3 Blank Screen Paradigm

The latest research has used a new paradigm—the blank screen paradigm—to study attentional refreshing processes. This paradigm utilizes eye movement data to describe internal attentional processes (Káldi & Babarczy, 2021). After visual stimuli are presented, a blank screen is displayed. The effectiveness of attentional refreshing in maintaining different types of information varies. For example, Alessandra (2018) used retro-cues to guide participants to refresh different types of information in an experiment and found that although attentional refreshing improved memory performance for all types of information, it produced more pronounced improvements for visual and spatial information compared to phonological information. However, this conclusion was based on situations where retro-cues guided participants to perform attentional refreshing. It remains unknown whether attentional refreshing has different effects on different types of information when participants refresh spontaneously. Additionally, some special types of information do not support attentional refreshing. For instance, Vergauwe et al. (2014) showed that compared to requiring participants to perform parity judgment tasks during memory maintenance (i.e., suppressing attentional refreshing), allowing attentional refreshing did not improve memory for letters in special fonts. Similarly, memory for unconventional characters decayed over time even when attentional refreshing was not suppressed during the maintenance period (Ricker & Cowan, 2010). In other words, attentional refreshing cannot facilitate the maintenance of these two types of items. A plausible explanation is that such special information can only be stored in sensory form and cannot form representations, and therefore cannot be refreshed (Camos et al., 2018). In summary, attentional refreshing can act on all information that can form representations, but its effects may differ for different types of information.

4.3 When to Use Attentional Refreshing

When both attentional refreshing and articulatory rehearsal are available, which strategy do people choose for memory maintenance? It is well known that humans have a tendency to avoid expending cognitive resources (Stanovich & West, 2000). This means that articulatory rehearsal, which consumes fewer resources, is the first option. However, attentional refreshing demonstrates its effectiveness in two situations.

One situation is when articulatory rehearsal is limited or ineffective, making attentional refreshing the preferred option for memory maintenance. Obviously, when memory information cannot be represented verbally or when participants are required to perform articulatory suppression, they will maintain memory through attentional refreshing. Additionally, when the phonological similarity of memory items is high, leading to poor articulatory rehearsal effectiveness, attentional refreshing will take over the maintenance system.

5 The Internal Process of Attentional Refreshing

As an internal psychological process, how does attentional refreshing operate, and what information receives priority for refreshing? This topic has been debated for a long time. Initially, cumulative forward-order refreshing, borrowed from articulatory rehearsal, was abandoned due to lack of support from experiments and computational models (Vergauwe et al., 2016; Vergauwe, 2018; Vergauwe et al., 2018). Subsequently, researchers sought two alternatives: parallel refreshing (Portrat & Lemaire, 2015) and prioritizing weakly activated information (Jafarpour et al., 2017; Lemaire et al., 2018). The core assumption of parallel refreshing is that the focus of attention can expand or shrink according to task demands (Cowan et al., 2012). Currently, this hypothesis has no clear conclusion, with both supporting and opposing evidence existing. The refreshing method that prioritizes weakly activated information appears to be the most realistic and has received support from magnetoencephalography and computational modeling studies. Additionally, unlike the aforementioned refreshing methods, experience-related stimuli can involuntarily capture individuals' attention during the refreshing process and thus receive priority refreshing (Thomas et al., 2016; Yin et al., 2019).

5.1 Cumulative Forward-Order Refreshing

Inspired by how articulatory rehearsal operates (Tan & Ward, 2008), refreshing was initially conceptualized in the TBRS model as occurring in a serial, cumulative forward-order manner. Individuals sequentially incorporated each item into a refreshing list according to the encoding order, with the focus of attention cycling from one item to the next, thereby sequentially enhancing the activation levels of list items (Barrouillet & Camos, 2012a; Loaiza & McCabe, 2012; Vergauwe et al., 2014).

However, experimental results do not support this view. Vergauwe (2018) used retro-cues to guide participants to refresh in three different ways (forward-order refreshing starting from the first position, forward-order refreshing starting from a random position, and random-order refreshing starting from a random position) to examine how different attentional refreshing methods affected letter recall performance. If refreshing occurs in a cumulative forward-order manner, guiding participants to refresh in different ways should impair recall. However, experimental results showed no significant differences in memory performance among the three refreshing methods, and all three impaired memory performance compared to the spontaneous refreshing condition. This suggests that attentional refreshing is likely not performed in a cumulative forward-order manner.

5.2 Parallel Refreshing

Since attentional refreshing does not occur in a cumulative forward-order manner, how does it operate? One alternative is that the focus of attention can expand to up to 4 items during refreshing according to task demands, enabling simultaneous refreshing of multiple items—this mechanism is called parallel refreshing. The concept of parallel refreshing originates from the hypothesis of Cowan et al. (2012), who proposed that attentional control ability is an important manifestation of individual differences. Individuals can flexibly control their focus of attention, concentrating on a single item under low cognitive load and expanding the focus to maintain multiple items to the greatest extent under high cognitive load.

Although lacking support from behavioral experiments, this parallel refreshing approach has received support from computational simulations. Portrat and Lemaire (2015) used a computational model based on the TBRS model to show that fitting real data with a cumulative forward-order refreshing method would require assuming that refreshing occurs extremely rapidly, completing one refresh within 10 ms, which is clearly unreasonable. If the focus of attention can be expanded to 4 items, a refresh rate of 40 ms per refresh can better fit real data (Vergauwe et al., 2014).

However, some evidence does not support parallel refreshing. In Oberauer' s (2002) study, participants needed to remember all numbers presented on the screen. After the numbers disappeared, an operation cue (e.g., +2) appeared at the location of one number, requiring participants to calculate and update that number in memory. After completing the calculation and update, participants pressed the spacebar to proceed to the next calculation and update. Results showed that participants responded faster when continuously calculating and updating numbers at the same location than when updating numbers at different locations. This suggests that participants can only focus their attention on one item. The debate over whether the focus of attention can expand to multiple items continues, and an in-depth discussion of this issue is beyond the scope of this article. In fact, attentional refreshing may occur too rapidly for traditional psychological methods to clearly distinguish whether it operates serially or in parallel.

5.3 Prioritizing Weakly Activated Items

Some studies provide new insights into serial refreshing, emphasizing the advantage of weakly activated items in the attentional refreshing process. Jafarpour et al. (2017) conducted an experiment requiring participants to memorize three types of images with different spatial cortical representations—faces, chairs (man-made objects), and fruits (natural objects). Using magnetoencephalography to decode brain activity during the memory maintenance period, they showed that only one image received prioritized processing during the maintenance phase, thereby enhancing recall performance. Analysis of event-related fields during memory encoding indicated that the item receiving prioritized refreshing was the item with the weakest activation during encoding. The authors proposed that prioritizing weakly encoded items for refreshing can protect them from interference during the maintenance period, while strongly encoded items can be recovered from long-term memory after the delay.

Lemaire et al. (2018) used the TBRS model to simulate seven refreshing process models under two conditions with single refresh times of 40 ms and 80 ms. These seven refreshing processes included: cumulative forward-order refreshing, random refreshing, refreshing only the last encoded item, refreshing only items below the activation threshold (similar to cumulative forward-order refreshing but stopping when all items are above the activation threshold), prioritizing the currently weakest activated item, probabilistic refreshing (the currently weakest activated item has a higher probability of being refreshed), and parallel refreshing. Simulation results showed that prioritizing the currently weakest activated item provided the best fit to real data. Additionally, the authors proposed two possible implementations for prioritizing weakly activated items. One is that participants quickly scan memory items before each refresh to identify the item with the lowest current activation. The other is that participants accumulate experience across multiple refreshing episodes during the experiment and schedule the refreshing process based on items and timing before refreshing. The authors suggested that these two implementations operate in different situations—the former consumes more cognitive resources, while the latter requires fewer cognitive resources, but which implementation is chosen depends on the cognitive resources available for the current task and the individual' s experience base.

5.4 Prioritizing Experience-Related Stimuli

The aforementioned refreshing methods reflect the general pattern of attentional refreshing when memorizing items without special meaning. However, some special stimuli may have unique advantages during refreshing. In the Multiple-Levels Framework of Auditory Attention (MFAA), individuals' attention can be guided not only by current goals but also by stimulus salience and experience (Addleman & Jiang, 2019). The retro-cue paradigm has confirmed that current goals can guide participants to perform attentional refreshing (Souza & Oberauer, 2016). Since stimulus salience is considered a characteristic of external attention (Chun et al., 2011) and attentional refreshing is an internal attentional process, stimulus salience does not affect the attentional refreshing process. So, are experience-related stimuli prioritized during attentional refreshing?

Thomas et al. (2016) confirmed that reward-related stimuli are prioritized during attentional refreshing and that corresponding stimuli recall performance is improved. Their experiment consisted of a learning phase and a working memory test phase. In the learning phase, participants were trained to establish associations between specific colors and values through color-score pairings. Specifically, four squares were presented at four locations on the screen, and participants selected one to click. The square at that location was then replaced by a colored stimulus, and the score obtained was presented. Four colored stimuli always corresponded to specific scores (-10, 0, 0, +10). The total score obtained by participants after the experiment could be converted into monetary rewards. In the working memory test phase, participants needed to memorize four stimuli presented on the screen (three stimuli without color and one stimulus corresponding to a previously learned color) and, after a certain time interval, judge whether a stimulus presented at the center of the screen was one of the previously memorized stimuli. Results showed that, with equivalent fixation time during encoding, participants' recall performance for high-value stimuli corresponding to the +10 score was better than for neutral stimuli corresponding to the 0 score, and recall for neutral stimuli was better than for low-value stimuli corresponding to the -10 score.

Additionally, Yin et al. (2019) confirmed that self-related stimuli are prioritized during attentional refreshing. In their study, participants first established associations between specific colors and three social labels—self, friend, and stranger—through an associative learning task in the learning phase. In the encoding phase, two colored dots of previously learned colors appeared at two non-adjacent vertices of an invisible regular octagon. Participants needed to remember the colors and locations of these two dots. Unlike previous studies, during the memory maintenance phase, participants needed to complete an additional dot-probe task. This task randomly presented two small vertical or horizontal dots at the location of one of the previously presented colored dots and required participants to judge whether the two small dots were horizontal or vertical. In the final recall phase, a black dot appeared at one of the eight locations of the invisible regular octagon, and participants needed to judge whether the location of the black dot matched either of the previously presented colored dots. Response times in the dot-probe task were used to measure the refreshing advantage of stimuli at corresponding locations during the attentional refreshing process. The rationale is that when attention is directed to a location stored in working memory, responses to external stimuli presented at that location become faster (Awh et al., 1998). Through this method, faster response times at locations of self-related stimuli in the dot-probe task indicate that self-related stimuli were prioritized during the working memory maintenance phase.

6 Summary and Outlook

Attentional refreshing is not only a mechanism for maintaining memory but is also closely related to information processing, making it a hot topic in working memory research. This article focuses on the mechanisms and internal processes of attentional refreshing, attempting to answer questions such as "How does attentional refreshing work, what types of information does it refresh, when is it used, and what is its mode of operation?" Attentional refreshing promotes and extends the activation level of information by retrieving it into the focus of attention. It does not depend on the phonological loop and can therefore act on all information that can form representations, though its effects may differ for different types of information, particularly showing more pronounced improvements for visual and spatial information. When articulatory rehearsal is limited or cannot maintain all information, attentional refreshing helps us better maintain working memory information. However, its dependence on attentional resources also makes attentional refreshing a process vulnerable to interference, limiting its use. Attentional refreshing most likely operates by prioritizing weakly activated items under normal circumstances, reflecting the efficiency of the working memory maintenance system. Additionally, some experience-related stimuli, such as reward-related and self-related stimuli, are prioritized by individuals. Finally, this article introduces several new research directions, hoping to inspire future research.

First, future research could further investigate whether attentional refreshing can affect memory precision. Memory accessibility describes the probability of retrieving specific information, while memory precision describes the degree of detail preservation when retrieving specific information. Past research has mostly focused on memory accessibility (Vergauwe & Langerock, 2017), typically distinguishing only whether memory information can be retrieved without examining the degree of detail preservation during retrieval. Thanks to the development of continuous report paradigms and mixture modeling, more and more research has begun to address memory precision (Zhang & Luck, 2008; Souza & Oberauer, 2015; Berens et al., 2020). In continuous report paradigms, participants need to indicate remembered items on a continuous scale (e.g., clicking on a color wheel to report the color of a memory item). This task requires continuous quantification of memory content during retrieval, rather than simply making yes/no decisions. In current refreshing research, most studies use retro-cues to examine the contribution of passive refreshing to memory precision, but the results are inconsistent (Gunseli et al., 2015; Israel et al., 2015; Souza et al., 2018; Ye et al., 2016). The inconsistency may be due to different manipulations across these studies in terms of the number of memory items, the number of retro-cue presentations, cue presentation methods, and cue reliability. Future research could systematically manipulate these variables to explore whether and under what boundary conditions retro-cues affect memory precision. Moreover, no research has examined the relationship between spontaneous refreshing and memory precision. Future studies could combine complex span tasks with continuous report paradigms to investigate whether spontaneous attentional refreshing can improve memory precision.

Second, further investigation is needed into how attentional interference or processing tasks during the maintenance period affect attentional refreshing speed. Past research has suggested that the impact of attentional interference or processing tasks on attentional refreshing mainly lies in occupying time available for refreshing. However, considering that memory retrieval difficulty increases over time, refreshing after interference or processing tasks also becomes more difficult. This means that the occupation of attentional resources not only reduces the time available for refreshing but may also slow down refreshing speed. Given that attentional refreshing occurs too rapidly for general behavioral experiments to test the impact of interference or processing tasks on refreshing speed, future research could change the parameters of how interference or processing tasks affect attentional refreshing in computational models to fit real data and explore whether interference or processing tasks affect refreshing speed.

Third, it is necessary to examine whether prioritizing weakly activated items is a reasonable attentional refreshing strategy under high attentional load conditions. When all encoded items can be maintained, prioritizing weakly activated items is a reasonable resource allocation strategy that allocates more resources to easily forgotten items and thereby improves working memory maintenance efficiency. However, when processing or interference tasks during memory maintenance demand such high attentional load that not all encoded items can be maintained, prioritizing weakly activated items may cause participants to abandon more easily memorable items in order to refresh easily forgotten items, thereby reducing memory maintenance efficiency. In experiments, people might be able to adjust their refreshing strategy through experience. However, when facing sudden interference in reality, accurately judging whether all memory items can be maintained is unrealistic. This means that the strategy of prioritizing weakly activated items is likely a double-edged sword: it provides an efficient maintenance method that maximizes the maintenance of all information under low attentional load conditions, but may cause more forgetting under high attentional load conditions. When attentional load is known to be low, participants typically use the strategy of prioritizing weakly activated items. Future research could use magnetoencephalography or the blank screen paradigm to compare participants' attentional refreshing methods under high- and low-load conditions to verify whether participants still use the strategy of prioritizing weakly activated items under high-load conditions. Alternatively, an unexpected high-load trial could be inserted in low-load conditions to explore whether prioritizing weakly activated items reduces memory maintenance efficiency when participants face sudden interference.

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