How does the internal attentional selection advantage in visual working memory arise? A perspective based on the retro-cue paradigm

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Abstract

Visual working memory is a core cognitive system for the short-term storage and online processing of visual information, and its information processing flexibility depends on the directional regulation of internal attention. The retro-cue paradigm is a key tool for exploring the relationship between the two; by presenting a cue after the memory array and before the probe test, it triggers the retro-cue benefit, which intuitively reflects the advantage of internal attentional selection. Based on the continuous resource model, this study systematically reviews relevant research and demonstrates that the formation of the internal attentional selection advantage is predicated on the degree of working memory consolidation, a prerequisite that determines the effectiveness of the retro-cue.

Building upon this, it is necessary to rely on sustained attention to maintain the stable activation of target representations and to optimize memory performance by improving the quality of information accumulation during the decision-making stage. Meanwhile, temporal dynamics, changes in memory items, cue variations, and external interference dynamically influence the effect of internal attentional selection by modulating the efficiency of working memory resource allocation and representational stability.

Accordingly, this study constructs an integrated cognitive model of the mechanisms underlying the internal attentional selection advantage and its interactions with influencing factors. Based on this model, future research should further focus on active inhibition mechanisms, complex stimulus processing, and the internal attentional characteristics of populations with neurodevelopmental disorders, thereby providing new perspectives for an in-depth understanding of the process by which internal attention flexibly manages information in visual working memory.

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Preamble

How Does the Internal Attentional Selection Advantage Arise in Visual Working Memory? A Perspective Based on the Retro-Cue Paradigm

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Abstract: Visual working memory (VWM) is a core cognitive system for the short-term storage and online processing of visual information. The flexibility of its information processing depends on the directional regulation of internal attention. The retro-cue paradigm is a critical tool for exploring the relationship between these two components. By presenting a cue after the memory array but before the probe test, this paradigm triggers a "retro-cue benefit," which intuitively reflects the advantage of internal attentional selection. Based on the continuous resource model, this study systematically reviews relevant research and demonstrates that the formation of the internal attentional selection advantage is predicated on the degree of working memory consolidation; this prerequisite determines the effectiveness of the retro-cue. Building upon this, stable activation of target representations must be maintained through sustained attention, and memory performance is optimized by improving the quality of information accumulation during the decision-making stage. Factors such as time course, changes in memory items, cue variations, and external interference dynamically influence the effects of internal attentional selection by modulating the efficiency of VWM resource allocation and representational stability. Accordingly, this study constructs an integrated cognitive model of the mechanisms underlying the internal attentional selection advantage and its interaction with influencing factors. Based on this model, future research should further focus on active inhibition mechanisms, complex stimuli processing, and the internal attentional characteristics of populations with neurodevelopmental disorders, thereby providing new perspectives for understanding the process of flexible information management in VWM via internal attention.

Keywords: Visual working memory, Internal attention, Internal attentional selection advantage, Retro-cue, Retro-cue paradigm

As a core component of high-level cognitive systems, Visual Working Memory (VWM) performs the critical functions of short-term storage and online processing of visual information. How its limited capacity adapts to the demands for information processing flexibility in cognitive tasks remains a central issue of long-standing interest to researchers. In complex cognitive scenarios, individuals often need to accurately filter and prioritize information relevant to the current task from multiple representations stored in VWM. This process relies on the directional regulation of internal attention. Unlike external attention, which focuses on external sensory stimuli, internal attention operates on representations generated or maintained within VWM. By dynamically adjusting the priority of these representations, internal attention keeps target information active while inhibiting interference from irrelevant information, ultimately optimizing behavioral performance [?].

How, then, can the effects of internal attentional selection be effectively isolated from VWM behavioral performance? The retro-cue paradigm is an effective experimental framework for manipulating internal attentional selection [?]. By presenting a cue pointing to a target item during the interval after the memory array and before the probe test, the paradigm prompts individuals to selectively direct their attention to the location of the target representation within VWM. Essentially, this involves the prioritized processing of specific memory representations during the maintenance phase after VWM encoding is complete. In this paradigm, the validity of the retro-cue modulates VWM performance. When the retro-cue is valid (pointing to the location of the item to be tested), memory performance is significantly better than in the neutral retro-cue condition (where there is no specific directionality); this phenomenon is known as the "Retro-Cue Benefit (RCB)" [?]. Conversely, when the retro-cue is invalid (pointing to a non-tested item), memory performance is impaired compared to the neutral condition, a phenomenon termed the "Retro-Cue Cost (RCC)." These differences in memory performance arise because the internal attentional selection triggered by the retro-cue activates both the shared attentional network (common to internal and external attention) and neural networks unique to internal attention, while also modulating activity in the sensory cortex related to VWM representations [?]. Thus, the RCB reflects the positive regulatory advantage of internal attention on target representations: internal attention can allocate VWM resources, directionally activate target representations and their corresponding neural encoding regions, and optimize encoding quality, thereby enhancing memory performance. In contrast, the RCC reflects the selection cost when internal attention deviates from the target. For instance, increased activity in neural regions associated with non-cued items may weaken the neural encoding strength of the target representation through resource competition or inhibitory regulation. Together, both confirm that internal attentional selection possesses both goal-directedness and resource allocation capabilities. However, unlike the RCC, which reflects the "dispersion of resources toward non-targets," the RCB more intuitively demonstrates the tilting of resource weights toward the target item. This allows the target representation to be processed preferentially at a lower cost and prospectively transformed into a representational format conducive to subsequent probing. This is precisely where the "advantage" of internal attentional selection lies. Therefore, the investigation of the internal attentional selection advantage is essentially an observation of the mechanisms generating the RCB [?].

Furthermore, the differences in resource allocation reflected by RCB and RCC during target selection can be robustly supported by the continuous resource model. This model emphasizes that continuous storage resources in VWM can be flexibly allocated, with memory items prioritized by internal attention receiving more resources [?]. The continuous resource model is used as a theoretical foundation because the effect of internal attentional selection is not a binary distinction of whether a memory representation is stored, but rather a gradient difference in representational quality and memory performance. Theoretically, this requires a model capable of describing the continuous changes in representational quality that occur with internal attentional selection. On this basis, the continuous resource model demonstrates unique advantages: it treats the noisiness of internal representations in VWM as an inherent property under limited resource constraints. This property is the cause of representational uncertainty, providing a plausible explanation for how internal attentional selection in the retro-cue paradigm alters that uncertainty. Specifically, internal representations in VWM are affected by neural noise, leading to random variations across trials that manifest as uncertainty at the representational level. Cognitive processing is not a direct readout of memory representation information but rather an inference based on these uncertain representations, where uncertainty information is progressively integrated during decision-making to guide behavior [?]. Within this framework, the continuous resource model can explain the magnitude and variation of uncertainty triggered by cues through gradient differences and fluctuations in resource allocation. It utilizes neural and behavioral indices to achieve a refined estimation of the resource trade-off between target and non-target representations.

It is evident that the core of internal attentional selection in VWM is the allocation of and competition for limited resources. In this "resource struggle," researchers believe that the functional utility of the retro-cue depends on four characteristics: the time course (critical temporal parameters of different VWM stages); splitting attention between multiple WM items (resource competition among multiple memory items); strategic control (individual adjustment of cognitive strategies); and resistance to distraction (resisting external interference to ensure the stability of target representations) [?]. Correspondingly, influencing factors can alter the effectiveness of retro-cues in modulating internal attentional selection. Existing research provides support for this; for example, the internal attentional selection advantage increases as the Cue-Test Interval (CTI) lengthens, reaching an optimal level at 400ms [?]. Moreover, the selection advantage varies with memory load, with the RCB under low memory load conditions being significantly higher than under high memory load conditions [?]. Furthermore, when multiple retro-cues are set in a task requiring individuals to allocate resources to several target items simultaneously, individuals can maintain prioritized processing of target items through inhibitory regulation of irrelevant information. This allows an RCB to still be generated under multi-cue conditions, though its effect size is markedly lower than in single-cue conditions [?]. Additionally, studies introducing masking or task interference during the VWM maintenance phase found that RCBs were generated in retro-cue conditions, with memory performance significantly better than in neutral cue conditions where interference was present [?, ?]. Accordingly, by synthesizing previous research, this study categorizes the factors influencing the internal attentional selection advantage into four dimensions: time course, memory item changes, cue variations, and external interference, which will be explored in detail subsequently. According to the aforementioned views, the generation of the internal attentional selection advantage is not dominated by a single element but is a relatively complex process.

Therefore, the reasons for differences in its performance cannot be generalized; they should be examined from a multidimensional perspective involving the interaction between core mechanisms and influencing factors.

分析。Shepherdson 等人（2018）通过操纵刺激材料（字母或单词）、记忆负荷（1~8 个项目），

Furthermore, research utilizing various CTIs (100/400/2000 ms) has found that when letters are presented simultaneously, the Retro-Cue Benefit (RCB) is observed in both memory accuracy and reaction times under cued conditions. Conversely, when words are presented sequentially, the RCB manifests only in reaction times, regardless of changes in CTI or memory load; no significant effect is observed in accuracy. While that study inferred that the absence of the RCB might stem from differences in the representation types of the stimulus materials, it overlooked the potential influence of the stimulus presentation format. Subsequently, Niklaus et al. (2019) employed either words or colored circles as memory items using a consistent sequential presentation method. By fixing the CTI (500 ms) and memory load (5-6 items) while adjusting stimulus intervals to alter task structure, their results consistently showed that the RCB appeared only in reaction times rather than accuracy. This suggests that the absence or attenuation of the RCB at the accuracy level involves not only stimulus representation and presentation modes but is also closely related to task structure and differences in processing mechanisms. Consequently, the present study attempts to construct a cognitive model by integrating the generation mechanisms and influencing factors of the internal attentional selection advantage. By synthesizing these internal correlations, we aim to provide critical support for clarifying the conditions and mechanisms under which the RCB is generated and optimized.

In summary, the emergence of the internal attentional selection advantage aligns with the perspective of a "subjective optimal strategy under resource constraints." That is, under the constraints of limited storage resources, individuals tend to process items—whether selected by internal attention or not—in a manner that is most beneficial to behavioral outcomes and convenient to execute (Fu, Wang, et al., 2020). However, in the process of achieving flexible management of information within Visual Working Memory (VWM), what specific factors lead to the generation, attenuation, or absence of the internal attentional selection advantage? Which factors influence the manifestation of this advantage across different retro-cue paradigms and their variants, and how do these factors regulate memory performance via retro-cues? In light of these questions, the author systematically reviews the generation mechanisms and influencing factors of the internal attentional selection advantage based on the retro-cue paradigm. This approach aims to provide a deeper understanding of how internal attentional selection impacts information maintained in VWM.

2 内部注意选择优势产生的机制

Existing research generally posits that the core function of the Retro-cue Benefit (RCB) lies in optimizing internal representations within Visual Working Memory (VWM), thereby enhancing memory performance. However, exploring the origins of the RCB requires more than just describing its functional outcomes; it necessitates clarifying the underlying process by which internal attentional selection advantages are realized (Fu, 2020). The two-stage prioritized processing model suggests that the generation of internal attentional selection advantages consists of two distinct phases: "internal attentional orientation and selection" and "representational state reconstruction" (Myers et al., 2017). The former phase relies on the dorsal frontoparietal attention network to lock onto target items and briefly activate their sensory representations. The latter phase depends on the synergistic action of the ventrolateral prefrontal cortex and the striatum to transform these sensory representations into behaviorally oriented representations (e.g., establishing the relationship between target features and key-press rules), thereby constructing a "perceptual representation-behavioral output" mapping. This model further contends that target localization and preliminary activation can be completed through brief neural activity following the presentation of a retro-cue, without requiring sustained attention. However, current cognitive neuroscience evidence indicates that maintaining representations with different priorities requires continuous allocation of attentional resources and functional coupling between specific brain regions (Yu et al., 2020), a phenomenon that is particularly evident under conditions involving multiple retro-cues or variations in retro-cue validity.

This suggests that the model' s description of the dynamic mechanisms during the "representational state reconstruction" phase is oversimplified, as it lacks the process of "sustained attention for the dynamic maintenance and regulation of representations." This process maintains the prioritized processing of target representations through dynamic resource allocation and interference suppression mechanisms, likely relying on continuous coupling between the frontoparietal attention network and the early visual cortex (Yu et al., 2020). Overall, refining this model would further clarify that the formation of internal attentional selection advantages is grounded in the sufficiency of VWM consolidation during the initial encoding stage. Its effectiveness depends on the support provided by sustained attention for the activation and state regulation of target representations during the VWM maintenance phase, ultimately enhancing memory performance by optimizing the quality of information during decision-making and output.

2.1 表征待命：记忆巩固充分性决定内部注意选择定向功能的发挥

Visual working memory (VWM) consolidation is the process of transforming transient visual input into stable representations. The sufficiency of this process is reflected in whether the memory representation reaches a steady state, with consolidation time (CT) serving as a critical metric for this status [?]. Consolidation sufficiency determines whether retro-cues can effectively guide internal attention for selection and orientation. According to the two-stage model of VWM resource allocation proposed by Ye et al. (2019), the early stage involves the automatic allocation of resources to memory items in a stimulus-driven manner, resulting only in low-precision representations. Once consolidation is sufficient, processing enters a late stage where individuals can flexibly adjust resource allocation based on task demands. Fully consolidated representations, once selected by attention, are less susceptible to interference or temporal decay [?], suggesting that only insufficiently consolidated representations benefit from retro-cues.

Research indicates that the consolidation of a single stimulus requires approximately 600-700 ms [?]. Using sequential presentation of memory materials, Luo et al. (2023) found that when the CT was 200 ms (leading to insufficient consolidation), a significant retro-cue benefit (RCB) emerged, markedly improving memory accuracy. Conversely, when the CT reached 700 ms (achieving sufficient consolidation), the RCB disappeared, and retro-cues had no significant effect on accuracy. The mechanism underlying this result is that sequential presentation forces VWM consolidation to proceed serially, with each item occupying attentional resources in turn. When the CT for a single item reaches the critical threshold (600-700 ms), all items obtain sufficient resources to form stable representations, leaving no room for retro-cues to provide further benefit. This mechanism also explains the findings of Niklaus et al. (2019); although they observed a recency effect in stimulus sequences, they found no significant RCB for the final item in terms of accuracy. Since the CT for the final item was approximately 950 ms, its consolidation sufficiency was much higher than that of other items (500 ms/item), making it difficult for retro-cues to further enhance performance. In contrast, Shepherdson et al. (2018) found no RCB for memory accuracy even when the CT for each word item was insufficient. The core reason was their use of gapless sequential presentation. The lack of an interstimulus interval hindered the transformation of transient memory into VWM. Not only was the neural activation of these representations quickly suppressed by subsequent items, making it difficult to form stable representations, but it may also have triggered mutual inhibition between neurons in the early visual cortex and verbal processing areas [?]. This ultimately led to the absence of an accuracy advantage for internal attentional selection. This further suggests that the attenuation of the RCB stems not only from full consolidation or a total lack of consolidation but also from the competition triggered by the consolidation process itself under sequential presentation conditions.

The aforementioned studies all utilized experimental designs with sequential stimulus presentation. However, this does not fully explain the attenuation of the RCB observed in classical retro-cue paradigms where stimuli are presented simultaneously [?, ?, ?]. Based on the two-stage model of VWM resource allocation, the stimulus presentation time per item (total presentation time divided by the number of items) during the early stage is a key component of CT. If this time is less than 100 ms per item, individuals find it difficult to actively allocate resources later, preventing an active trade-off between the precision and quantity of VWM representations [?].

In such cases, retro-cues can compensate for insufficient early processing by reactivating target-related neural representations, thereby generating an RCB. Building on this, Luo et al. (2023) presented four colored squares simultaneously for 400 ms (100 ms/item) and set a short CT of 200 ms/item and a long CT of 700 ms/item. They found that the long CT significantly weakened the RCB due to sufficient representation consolidation. This indicates that during simultaneous presentation, VWM consolidation proceeds via parallel processing, and the generation of the RCB is jointly regulated by VWM capacity limits and the available CT window.

Additional electroencephalographic (EEG) evidence suggests that low-complexity features, such as color, can be rapidly consolidated through parallel processing in the early visual cortex, with a VWM consolidation bandwidth supporting two items simultaneously. In contrast, high-complexity features, such as orientation, rely on serial processing in the parietal lobe, with a bandwidth supporting only one item [?]. Does this imply that orientation features are more likely to yield an RCB due to limited consolidation sufficiency when multiple stimuli are presented simultaneously? Recent studies, however, show that even when CT meets the conditions for RCB generation, the RCB for orientation features remains weaker or absent compared to color features [?, ?]. This may be because different types of retro-cues vary in their effectiveness for extracting orientation features. For instance, the efficiency of extracting orientation after locating an object with a spatial retro-cue is lower than when using a color retro-cue. Furthermore, unlike the high salience of color, the processing of orientation requires higher precision (e.g., angular differences), which further limits the manifestation of the RCB. Evidently, the modulation of internal attentional selection by consolidation sufficiency in classical retro-cue paradigms is also constrained by VWM load, memory item features, and the type of retro-cue used.

From a neurocomputational perspective, during the maintenance phase of VWM representations, consolidation sufficiency determines stability by modulating encoding precision in the early visual cortex and attentional resource allocation in the frontoparietal network. Although the event-related potential (ERP) study by Liu, Yin, et al. (2024) did not directly employ a retro-cue paradigm, it revealed the mechanism by which consolidation sufficiency regulates VWM neural representations. When consolidation is insufficient, although initial encoding in the early visual cortex begins, the efficiency of distractor inhibition is weak. This is evidenced by a reduced amplitude of the distractor positivity (P_D) component and a significant enhancement of the $N2$ posterior contralateral ($N2pc$) component, indicating that distractors more easily capture attention and that the frontoparietal network must prioritize resource allocation to the consolidation of target representations [?]. This pattern suggests that during the maintenance phase, individuals must perform initial encoding for all items; insufficient consolidation leads to fragile early encoding and intense resource competition. Retro-cues can compensate for the lack of early consolidation resources and extend the consolidation process by enhancing synchrony within the target-related frontoparietal network. Conversely, when consolidation is sufficient, target representations reach a highly stable state, and the frontoparietal network shifts toward active distractor inhibition. In this state, it is difficult for retro-cues to intervene in already saturated neural processing, precluding further optimization of the representation.

In summary, the attenuation of the RCB is not a simple behavioral effect but the result of dynamic competition between early visual cortex encoding bandwidth, frontoparietal regulatory mechanisms, and attentional inhibition. Although memory consolidation does not directly belong to the processing stage guided by retro-cues, it serves as a prerequisite. By shaping the stability and resource availability of representations in the early stages, consolidation plays a critical role in determining the allocation of limited cognitive resources and can be regarded as a fundamental condition for the emergence of the RCB.

2.2 状态维持：持续注意支持对记忆表征的激活与可访问性的调控

Sustained attention refers to the control process by which an individual maintains attention and engagement in a relatively monotonous task over time (Wang et al., 2025). In the retro-cue paradigm, researchers often employ masking or distractor tasks to investigate the role of sustained attention in generating the internal attentional selection advantage. This role varies depending on the type of retro-cue; however, such differences are not determined by the retro-cue itself, but rather by the amount of information evoked at the internal representation level and the resulting changes in regulatory complexity.

Based on the targets of internal attention, retro-cues can be classified into two categories: dimension-based and object-based. The former guides internal attention to focus on a feature dimension shared by all memory items (e.g., color), while the latter directs attention to a specific object through spatial location or object-specific features (e.g., the color blue). Dimension-based retro-cues are global in their mode of attention allocation, requiring feature comparison and dimensional filtering across all items in memory. This type of cue only reduces the amount of information that must be retained within a single representation by decreasing the informational weight of non-target features to optimize the allocation of attentional resources, thereby making target features easier to prioritize during subsequent retrieval. Research has found that regardless of the length of the Stimulus Onset Asynchrony (SOA) between the retro-cue and the distractor, interference significantly weakens the Retro-Cue Benefit (RCB) for dimension-based cues (Liu et al., 2023). This suggests that sustained attention is a necessary condition for the emergence of their internal attentional selection advantage.

Liu et al. (2023) proposed that following a retro-cue, Visual Working Memory (VWM) processing consists of two stages: attention deployment and prioritized information maintenance. The attention deployment stage occurs shortly after the presentation of the retro-cue, during which attention must be directed toward task-relevant features and VWM resources must be redistributed. The appearance of a distractor at this stage disrupts sustained attention, rendering the individual unable to effectively utilize the retro-cue to prioritize information within specific feature dimensions. This explains the finding in their study that perceptual interference directly eliminated the dimension-based RCB at short SOAs.

At long SOAs, even though attention deployment has been completed, distractors still weaken the RCB (Liu et al., 2023). This indicates that dimension-based retro-cues also rely heavily on sustained attention during the subsequent prioritized information maintenance stage. At the neural level, the presence of distractors may disrupt the functional coupling between the frontoparietal network and the early visual cortex, thereby affecting the redistribution and maintenance of attentional resources and reducing the stability and accessibility of target representations (Ülkü et al., 2025; Riddle et al., 2024).

In contrast, previous studies have suggested that distractors generally do not weaken the RCB for object-based retro-cues (Hollingworth & Maxcey-Richard, 2013; Makovski & Pertzov, 2015; Rerko et al., 2014), and their dependence on sustained attention is stage-specific. When the SOA is short, sustained attention is a necessary condition for successful internal attentional orientation and selection. When the SOA is long, the retro-cue can be maintained long enough in the absence of interference to complete VWM resource redistribution; at this point, distractors have no significant effect on the RCB (van Moorselaar et al., 2014). Evidence for this is provided by joint EEG-eye-tracking research: object-based retro-cues can rapidly integrate spatial location and feature information. This is evidenced by a significant lateralization of alpha waves (8–12 Hz) in the parieto-occipital region 200 ms after the retro-cue appears, accompanied by a gaze bias toward the target object's location and an observed spread of attention between different features of the same object (Printzlau et al., 2022). However, not all object-based retro-cues can rapidly generate an RCB and become independent of sustained attention. Subsequent studies have confirmed that the processing complexity of different forms of object retro-cues significantly alters the dependence of the internal attentional selection process on sustained attention. For example, Guo et al. (2025) used four rectangular bars with different orientations and colors as memory stimuli. They found that color-based object retro-cues (squares matching the target object' s color) could generate a stable RCB within 50–200 ms due to their stimulus-driven direct recognition advantage, requiring low sustained attention. Conversely, orientation-based object retro-cues (bars matching the target object' s orientation) required comparing the cue orientation with all memory items. This process consumes substantial top-down cognitive resources, directly competing for the attentional resources used to optimize memory representations. Consequently, it not only takes approximately 500 ms for the RCB to emerge but also requires more persistent sustained attention to ensure the generation of the internal attentional selection advantage. Similarly, digit-based object retro-cues lack an RCB because processing the mapping between digits and memory item locations consumes additional cognitive resources (Berryhill et al., 2012). Thus, if the processing of an object retro-cue involves complex cognitive operations, its demand for sustained attention during internal attentional selection increases significantly (Berryhill et al., 2012). Notably, some studies have found no significant difference in memory precision between object-based retro-cues with distractors and no-retro-cue conditions with distractors, suggesting that distractors do not destroy the original VWM representation (Ye et al., 2020). Furthermore, in the aforementioned behavioral studies, although distractors weakened the RCB for dimension-based retro-cues, they did not significantly increase memory bias in neutral retro-cue conditions (Liu et al., 2023). This further clarifies that the weakening of the RCB stems from the demand for sustained attention during cognitive processing rather than damage to the representation by the distractor.

The necessity of sustained attention is also supported by cognitive neurophysiological research. Paluch et al. (2025) employed a double retro-cue paradigm and recorded the activity of image-selective neurons in the medial temporal lobe (MTL). They found that after the first retro-cue, MTL neurons exhibited sustained firing for both cued and non-cued items. When the second retro-cue appeared and the non-cued item was still not selected as the target, the neuronal firing intensity decreased but remained significantly higher than baseline. This indicates that non-cued items do not disappear or become "silent" but maintain their accessibility through weak sustained firing. Combined with findings that sustained firing intensity is closely related to VWM performance (Daume et al., 2024), these results confirm that sustained neural activity is a universal mechanism for information storage. Moreover, the strength of this activity is modulated by shifts in the focus of attention and is correlated with representation quality. Sustained attention allows the priority-based differences in neural activity during the maintenance phase to remain stable, preventing a reduction in the gap between target and non-target representations regarding accessibility and decision-making utility, which would otherwise affect the generation of the RCB. This strongly refutes the view from earlier studies that "sustained attention is unnecessary in internal attentional selection"—the idea that once memory priority is locked, representation restructuring is immediately completed, and memory representations are stably retained in a "silent state" without the need for continuous neuronal firing or sustained attention (Myers et al., 2017). In fact, the limitation of this view lies not only in its one-sided assumption of a "silent state" for representations but also in its neglect of the dynamic and fragile nature of representational restructuring. Priority locking and subsequent restructuring do not constitute a final state that can automatically resist subsequent interference. EEG research by Gresch et al. (2025) shows that when VWM representations and their corresponding response plans (prospective behavioral plans bound to the target representation) are disturbed during the maintenance phase, the previously established internal attentional selection advantage weakens significantly. In such cases, the RCB cannot be maintained solely through a one-time restructuring; instead, internal attention must re-select the VWM representation and response plan after the interference.

During this re-selection process, the posterior alpha-wave lateralization associated with visual representation quickly reappears to achieve attentional reorientation. Meanwhile, the central beta-wave (13–30 Hz) lateralization associated with the response plan is continuously enhanced until the probe stage to maintain the availability of the response plan. Even in the absence of interference, visual selection signals are transient, whereas response plan signals persist (Gresch et al., 2025). It should be clarified that although alpha-wave lateralization is an indicator of rapid attentional orientation, it does not directly regulate representation quality, nor can it fully determine behavioral performance (Mössing & Busch, 2020). Therefore, not only must the response plan remain available under the regulation of sustained attention, but the maintenance of VWM representation quality also depends on the involvement of sustained attention.

In summary, behavioral and neural evidence consistently demonstrates that sustained attention, as a control mechanism, not only plays a key role in the early deployment stage of internal attentional selection but also supports the maintenance and reconstruction of the internal attentional selection advantage over time or under interference. It achieves this by stabilizing the priority-based accessibility of representations and the state of response plans. Consequently, sustained attention is indispensable for the generation and stability of the RCB.

2.3 决策输出：信息积累质量驱动内部注意选择行为表现的优化

In the process of memory cognition, decision-making is not an instantaneous event; rather, it is a process in which an individual progressively accumulates response evidence until a preset decision threshold is reached, thereby triggering a decision response (Shepherdson et al., 2018). Research on internal attentional selection indicates that if the quality of information accumulation is low, the rate of evidence accumulation slows down, leading to prolonged reaction times and decreased accuracy (Souza, Rerko, & Oberauer, 2016). Retro-cues are required to regulate the evidence accumulation process, enhance the quality of decision-making information, and optimize visual working memory (VWM) performance.

At the cognitive level, the core mechanism underlying the advantage of internal attentional selection lies in the separation of cognitive stages that might otherwise overlap, thereby creating the necessary conditions for the sufficient accumulation of target information. Ye et al. (2020) verified this mechanism by manipulating the relationship between retro-cues and probe presentation.

结果显示，正常回溯线索条件下（线索先于探测测试呈现）RCB 显著，个体记忆表现最优；而

When retro-cues and probes are presented simultaneously, individual VWM performance is significantly lower than under normal retro-cue conditions. This suggests that the synchronized presentation of the retro-cue and the probe causes internal attentional resource reallocation and decision-making processes to overlap in time. Consequently, limited attentional resources are consumed by competition between dual processes, thereby weakening memory representation and decision quality. Conversely, when the retro-cue precedes the probe, attentional allocation and decision execution unfold sequentially. This temporal separation reduces resource competition' s interference with information accumulation and enhances the quality of information available during decision-making, resulting in an internal attentional selection advantage—a phenomenon also known as the cognitive separation hypothesis of the decision stage. Simultaneously, the retrieval-lead hypothesis explains this mechanism from another perspective. Souza, Rerko, and Oberauer (2016) employed an experimental design where the presentation of the decision problem was delayed until the probe test appeared. This required individuals to simultaneously complete response selection (judging and choosing the correct response mode) and response execution (specific motor output) during the probe stage. Under these conditions, the retro-cue can only guide the individual in target retrieval but cannot facilitate response selection due to the absence of decision rules. Results showed that even with delayed decision problems, retro-cues produced a significant Retro-cue Benefit (RCB).

This design separates target retrieval from response selection in time, allowing the retro-cue to enhance the integrity of information accumulation by providing a "dedicated time window" for target retrieval. The retrieval-lead hypothesis thus posits that the key to the RCB lies in the retro-cue securing an opportunity for target retrieval, enabling individuals to retrieve the target in advance while delaying other forms of cognitive processing. This avoids the information incompleteness and internal interference caused by initiating a decision before retrieval is finished. Although both hypotheses share commonalities—both establish a sequential information processing flow through retro-cues to prioritize limited attentional resources toward the evidence accumulation required for decision-making—they differ in two key aspects. First, they offer different perspectives on the separation of processing stages: the cognitive separation hypothesis emphasizes reducing resource competition to decrease information loss, while the retrieval-lead hypothesis focuses on ensuring retrieval sufficiency to improve information integrity. Second, they differ in the content of information accumulation: following a retro-cue, the cognitive separation process allows for pre-decision preparations (attentional allocation and response selection), whereas the retrieval-lead process primarily involves the accumulation of representational information without the possibility of response planning. Therefore, the two hypotheses support the generation of internal attentional selection in a complementary rather than conflicting manner.

At the neurophysiological level, internal attention regulates representational priority by modulating cortical excitability. This facilitates the completion of the perceptual representation-to-behavioral response mapping, upgrading information accumulation from initial feature-selection information into decision evidence capable of triggering a response.

Echeverria-Altuna et al. (2025) found that under the guidance of valid retro-cues, occipital α oscillations—serving as tracking indicators for spatial location representations—exhibit power attenuation contralateral to the cued item' s location, quickly locking onto target information. Simultaneously, central μ/β oscillations (8-30 Hz), acting as neural markers for response planning priority regulation, initiate power modulation contralateral to the responding hand, establishing a mapping between location perception and the response hand. When the cue-to-target interval (CTI) is extended, a "priority reversal" occurs in both α lateralization and μ/β power, shifting from prioritizing the cued item to the non-cued item. Notably, the α reversal occurs significantly earlier than the μ/β reversal; the two dissociate temporally and flexibly adjust priorities according to CTI changes. This indicates that internal attention can independently and dynamically regulate VWM representations and response plans (Echeverria-Altuna et al., 2025). In contrast, under invalid retro-cue conditions, individuals struggle to extract the association between target location/features and response plans because the cue cannot predict the probe item. Consequently, no significant lateralized modulation of α or μ/β oscillations is observed (Echeverria-Altuna et al., 2025).

Furthermore, invalid retro-cues are more likely to trigger competition between goal-driven voluntary attentional regulation and stimulus-driven involuntary regulation; however, this does not necessarily lead to a failure in decision information accumulation. EEG research indicates that mid-frontal θ (4–7 Hz) power increases as cognitive control demands rise during this competition. This θ enhancement is not accompanied by a preferential selection of non-target items but is significantly synchronized with a temporal delay in the prioritized processing of the target item (Ester & Nouri, 2023). This reflects that mid-frontal θ does not selectively manipulate specific representations but rather regulates competitive relationships through cognitive control, synchronously modulating the timing of target processing to stabilize the target representation and prevent stimulus-driven interference from deviating the selection. Moreover, once the target representation is successfully selected, higher θ activity is associated with faster subsequent response initiation (Ding et al., 2024). Thus, mid-frontal θ optimizes decision preparation by regulating competition, ensuring accurate and efficient decision-making. In summary, during the VWM decision output stage, the internal attentional selection advantage is generated by retro-cues that establish a sequential information processing flow. This completes the perception-behavior mapping and integrates representational and response selection information into comprehensive decision evidence, collectively enhancing decision information quality and output efficiency while optimizing behavioral performance.

Overall, the three core points mentioned above synergistically explain the mechanism underlying the RCB. Based on the continuous resource model, this mechanism can be summarized as follows: internal attention utilizes retro-cues to dynamically re-weight and continuously regulate limited resources, efficiently utilizing representational information during the decision stage. From the perspective of memory consolidation, this process is not an instantaneous state transition but a continuous progression of incremental resource investment and sustained reduction in representational uncertainty. During the early stages of stimulus presentation, sensory signals and VWM resources coexist in a state of dynamic integration, allowing representations to consolidate rapidly, though they remain limited by memory load. As sensory signals decay, representational precision decreases due to noise diffusion. At this point, the appearance of a retro-cue triggers a reallocation of resources and integrates residual sensory information, thereby extending the consolidation of the target representation and keeping it within a range that can be further modulated and optimized by neural gain (Tomić & Bays, 2024).

This also implies that retro-cues can improve existing representational quality by focusing or reallocating resources. During the maintenance phase, the role of sustained attention is similarly reflected in this continuous resource regulation process. The key lies not in changing the total amount of resources, but in stabilizing and maintaining priority-based differences in resource allocation among different memory items. Research by Li et al. (2025) supports this view, finding that overall resource levels correlate with activity in a distributed frontal-parietal-temporal network during the maintenance period, while the degree of resource prioritization depends on the bilateral superior precentral sulcus (sPCS) and the right posterior inferior temporal cortex (PIT). Specifically, trial-by-trial fluctuations in prefrontal cortex (PFC) activity, particularly in the sPCS, predict differences in the decoding accuracy of memory items with different priorities in the visual cortex. Combined with existing evidence of PIT involvement in visual attentional control (Stemmann & Freiwald, 2019), this suggests that sustained attention relies on an extended frontal-parietal-temporal control network to stabilize priority-based resource allocation and representational quality differences via top-down feedback signals. Additionally, the study found that cue-triggered resource reallocation and its accompanying neural gain modulation reduce the representational uncertainty of high-priority items, which further translates into faster response times and smaller memory errors, revealing a continuous mapping from internal representational quality to behavioral advantage. Related EEG studies have observed that after retro-cue presentation, the central parietal positivity (CPP) exhibits gradual accumulation dynamics before decision initiation, with its accumulation slope increasing alongside improvements in representation extraction efficiency and decision speed. This provides complementary evidence that during the decision stage, internal representational information is transformed into behavioral output through a progressive evidence accumulation mechanism (van Ede & Nobre, 2024). In conclusion, consolidation sufficiency, sustained attention, and decision information respectively reflect the investment, maintenance, and transformation of continuous yet limited VWM resources across different processing stages.

It is worth emphasizing that the continuous resource model and state-based models are not mutually exclusive. While state-based models focus on the transitions of memory items between different representational states, the three core mechanisms—consolidation sufficiency, sustained attention, and decision information—respectively constrain the establishment, stable maintenance, and post-reactivation reliability of these states. The continuous resource model reveals the mechanism by which representational quality is continuously regulated during processing, whereas state-based models clarify the transition paths of memory representations. Furthermore, processing bottlenecks in VWM can occur at different levels, and different models provide complementary explanations within the multi-level functional system of VWM (Ngiam, 2024). In this sense, the continuous resource model can be integrated with other VWM models under various experimental conditions to jointly provide theoretical support for internal attentional selection mechanisms. Therefore, the mechanistic framework proposed in this paper not only possesses explanatory power across theoretical models but also provides theoretical support for a systematic understanding of the factors influencing the RCB.

3.1 时间进程

The temporal dynamics of the Retro-cue Benefit (RCB) represent the external manifestation of the implicit dynamic changes in internal attention. These temporal variations are primarily concentrated in three key intervals: the Retro-cue Interval (RI), which is the duration between the memory array and the presentation of the retro-cue; the Stimulus Onset Asynchrony (SOA); and the Cue-to-Target Interval (CTI).

First, the timing of retro-cue presentation differentially modulates the efficiency of internal attentional selection by altering the cognitive processing sequence of Visual Working Memory (VWM). As a core indicator of the timing of retro-cue presentation, the RI influences the effectiveness of top-down attentional control. Early retro-cues provide individuals with sufficient time before the probe test to deploy top-down attentional modulation signals, thereby strengthening target representations. In contrast, late retro-cues lack sufficient processing time, making it difficult to effectively initiate internal attentional modulation and the coordinated activity of associated brain networks. In a study by Kuo, Yeh, et al. (2011), two retro-cue conditions were established: an early retro-cue presented 200 ms after stimulus disappearance for a duration of 700 ms before the test phase, and a late retro-cue presented 800 ms after stimulus disappearance for only 100 ms before the test. The results indicated that individuals in the early retro-cue condition exhibited higher accuracy and shorter reaction times in internal attentional selection. Furthermore, early retro-cues significantly enhanced the functional connectivity between the bilateral occipital visual cortex and the right middle frontal gyrus (MFG) and frontal eye fields (FEF), with frontal activity temporally preceding occipital activity. This strengthened functional coupling within the fronto-occipital network facilitates information transmission and integration, providing a neural foundation for enhanced top-down attentional control (Kuo, Yeh et al., 2011). Additionally, the facilitatory effect of early retro-cues on top-down control effectively alleviates the difficulty of detecting changes in feature binding during the perceptual comparison stage. For instance, Kuo, Rotshtein, et al. (2011) found that under late retro-cue conditions, accuracy for feature-binding change detection was significantly lower than for single-feature change detection; however, under early retro-cue conditions, there was no significant difference between the two. The difficulty in detecting feature-binding changes stems from the fragile nature of relational information involving multi-feature combinations, which is susceptible to inter-item interference during perceptual comparison. Because late retro-cues lead to delayed attentional modulation, they require additional activation of the right inferior frontal gyrus (IFG) and anterior cingulate cortex (ACC), as well as enhanced functional connectivity between the right superior parietal lobule (SPL) and these regions to mitigate conflict (Kuo, Rotshtein, & Yeh, 2011). This neural activity suggests that late retro-cues result in incomplete cognitive segregation, forcing individuals to rely on the conflict-monitoring functions of the frontoparietal network to alleviate resource competition during the probe stage. Such additional cognitive regulation not only consumes more resources but also fails to fully offset the disadvantages of insufficient cognitive segregation, ultimately leading to decreased behavioral efficiency.

Second, the temporal progression modulates the protective mechanism of retro-cues on VWM representations. Numerous studies have confirmed through temporal manipulation that retro-cues protect cued items from memory decay over time (Sahu & Tseng, 2021; Matsukura et al., 2007). Representations in VWM vary in their temporal stability; retro-cues shift resource allocation from a shared distribution across all items to a prioritized support of cued items, thereby slowing the decay of target representations (Pertzov et al., 2013; Poth, 2020). Schneider et al. (2016) identified this protective mechanism by observing non-cued items, noting that the RCB did not emerge when the CTI was 300–400 ms. However, when the CTI was 600 ms and extended to 1800 ms, behavioral performance significantly improved and the RCB gradually strengthened. Simultaneously, processing conflict triggered by non-cued items progressively weakened, as evidenced by a decrease in the N450 component. Furthermore, the contralateral suppression of alpha waves in the parieto-occipital region gradually strengthened and remained stable, with its intensity positively correlating with the rate of N450 attenuation. This demonstrates that a sufficient CTI can reduce the loss of memory resources by inhibiting competition between irrelevant representations. Subsequent research has also found that decayed target representations can gradually recover as the CTI lengthens, a process accompanied by enhanced functional connectivity in the alpha frequency band between the MFG and the right inferior parietal lobule (IPL). The rate of increase in connectivity strength is positively correlated with the rate of information recovery, suggesting that the coordinated activity of the frontoparietal network is the neural basis for retro-cues to reverse memory decay and achieve RCB as the CTI changes (Ester et al., 2018). Moreover, in studies where external perceptual interference is introduced after the retro-cue, the modulating role of the SOA is equally critical; a sufficient SOA allows the retro-cue to protect and stabilize the quality of target representations, reducing the impact of external interference (Han & Ku, 2022; Pertzov et al., 2013). Schneider, Barth, Getzmann, et al. (2017) further confirmed that when the $SOA \geq 500$ ms, the amplitude of the parietal negative slow wave (NSW) under retro-cue conditions is significantly lower than under neutral cue conditions. This reflects a release of cognitive resources triggered by a reduction in VWM load, an effect that is time-dependent, as the difference in NSW amplitude only becomes significant when the SOA exceeds 500 ms. This is consistent with previous findings suggesting that the RCB reaches its optimum at an SOA of 500–600 ms (Van Moorselaar, Gunseli et al., 2015).

3.2 记忆项变化

In retro-cue paradigms and their variants, current research primarily investigates how memory load and perceptual features of memory items influence the effectiveness of internal attentional selection.

On one hand, memory load influences the utility of retro-cues, as well as the quality of information entering the decision-making process and non-decision time, by altering internal interference between memory items. Existing studies have demonstrated that increased memory load reduces both the speed and accuracy of recognition strategies [?, ?, ?, ?, ?, ?].

Retro-cues can alleviate the difficulty of information maintenance and processing by clarifying the direction of internal attentional allocation. The operational mode of these cues varies with load: at low loads, they facilitate target memory, whereas at high loads, they inhibit distractors [?, ?]. This process is dynamically related to the function of the right intraparietal sulcus (IPS). Under low-load conditions, valid retro-cues can eliminate load-sensitive activation in the right anterior IPS, thereby strengthening attentional selection for target items. Under high-load conditions, residual representation activation of non-target items persists in the right posterior IPS; in such cases, retro-cues must maintain the Retro-Cue Benefit (RCB) by inhibiting interference from non-target items [?, ?]. It should be noted that the RCB does not increase continuously with load. By setting memory loads of 2, 4, and 8 items, Shepherdson et al. [?] found that when the number of items exceeds the capacity of visual working memory (VWM), the RCB is severely weakened, while invalid retro-cues trigger a significant Retro-Cue Cost (RCC).

This suggests that excessive memory load exacerbates the depletion of VWM resources. As interference between items increases during storage and retrieval, confusion or errors regarding decision-relevant information also rise, leading to a decrease in RCB and an increase in RCC. Furthermore, elevated memory load reduces the drift rate (reflecting representation quality) and prolongs non-decision time (reflecting the efficiency of representation retrieval) [?, ?, ?]. This indicates that memory load influences decision-making by altering the efficiency and quality of information accumulation. High memory load implies a greater volume of information must be retained in VWM, which may degrade the quality of individual representations, consequently extending the time required for individuals to judge memory representations during the probe stage. Especially in contexts requiring both speed and accuracy, increased memory load makes the task more difficult, thereby hindering the generation of the RCB.

On the other hand, the perceptual features of memory items influence the RCB by modulating the selective maintenance mechanism of internal attention [?, ?]. Sasin and Fougnie [?] noted that internal attention can selectively maintain VWM representations at the feature level, granting prioritized processing to cued features; however, this process is not necessarily accompanied by the effective inhibition of uncued features.

Chen, Ye, et al. [?] further explored this phenomenon. Their research found that when a retro-cue prompts one feature of an object while requiring another feature to be ignored, simple features (such as color or simple shapes) are more easily maintained actively than complex features (such as polygons) when serving as the cued feature, thereby eliciting a more significant RCB. However, when simple features serve as uncued features, they are more difficult to ignore or inhibit. Even when these simple features reappear as irrelevant features in subsequent search tasks, they still capture attention and generate significant interference, thus weakening the RCB. Conversely, complex features do not easily produce such interference effects when they are uncued, resulting in a more significant corresponding RCB. This suggests that variations in the RCB can be driven by the perceptual attributes of memory items through the modulation of internal attention' s selective maintenance mechanism. This difference in selective maintenance can fundamentally be explained by the degree of integration and resource demands triggered by different feature attributes. ERP evidence shows that highly integrated multi-feature objects exhibit higher processing efficiency during the encoding and selection stages and form more stable neural representation states during the maintenance stage. This is characterized by a reduction in the posterior positivity contralateral (PPC) during encoding, an enhancement of the N2pc during the attentional selection stage, and more stable contralateral delay activity (CDA) during the maintenance stage [?, ?, ?]. Moreover, an increase in the overall complexity of memory items is accompanied by an enhancement of the occipital P2, suggesting that posterior brain regions must invest more neural resources to complete the sensory filtering and encoding of complex stimuli [?, ?]. Taken together, these studies provide a unified explanation for changes in the RCB: simple features benefit rapidly when cued due to high integration efficiency, but they are also harder to remove when uncued, continuing to occupy resources and weakening the RCB. In contrast, complex features rely on attentional processing to integrate detailed information, which not only requires more attentional resources but also results in lower integration efficiency and representational stability. Consequently, when complex features are uncued, they are more easily decayed or removed from VWM, reducing subsequent resource competition and interference, and ultimately enhancing the RCB. Furthermore, a dynamic interaction exists between memory item features and internal attentional selection: as time progresses and task requirements change, internal attention adjusts based on the importance and relevance of the memory item features.

3.3 线索变化

Retroactive cues (retro-cues) typically influence the selection, regulation, and maintenance of specific information by internal attention through variations in both cue type and cue quantity. First, retro-cues can be categorized across two major dimensions: cue validity and the attributes of the selected object. Different types of retro-cues exert differential effects on internal attentional selection by modulating attention allocation strategies and neural activity patterns within visual working memory (VWM). Researchers classify cues as valid or invalid based on whether the cued item matches the final probe target. Depending on the research objectives and experimental design, researchers can adjust the probability of a valid retro-cue appearing in a task, referred to as cue reliability. Fully reliable retro-cues (100% validity) transition the cued item into an active state, making it more easily remembered by the individual [?].

Under high-reliability conditions, individuals adopt proactive attentional and memory strategies, prioritizing the allocation of cognitive resources to the cued item while weakening or removing non-cued items from VWM. In such cases, probing a non-cued item results in a substantial retro-cue cost (RCC) [?]. Conversely, under low-reliability conditions, individuals employ more flexible strategies, maintaining attention on non-cued items while focusing on the cued item to manage the uncertainty of the target appearing in a non-cued location. Related ERP research indicates that when retro-cue reliability is 50%, the Contralateral Delay Activity (CDA)—which reflects the load of attended information maintained in VWM—shows significant differences only immediately prior to the presentation of the probe stimulus. However, when reliability reaches 80%, significant CDA differences emerge early after the retro-cue onset, suggesting that non-cued items are more readily removed from VWM under high-reliability cues [?]. When reliability further drops to 20%, CDA differences are no longer significant, indicating that individuals maintain representations of both cued and non-cued items in VWM without abandoning the active maintenance of non-cued information [?]. Thus, the modulation of retro-cue reliability influences the effectiveness of internal attentional selection, allowing individuals to strategically adjust the maintenance of information in VWM based on the level of reliability.

In addition to classification by validity, the aforementioned dimension-based and object-based retro-cues trigger feature-based attention (FBA) and object-based attention (OBA), respectively, which also differ in their impact on internal attention. Research on FBA has shown that when retro-cues prompt the same feature dimension across different objects, the resulting retro-cue benefit (RCB) is significantly larger than when prompting different feature dimensions of different objects. This suggests that FBA is more efficient at allocating attention to the same feature dimension within VWM and can dynamically adjust the relative priority of different feature dimensions in multi-feature objects [?]. However, [?] found contrasting results: memory accuracy for uncued features within the same object was higher than for the same feature dimension in an uncued object. Consequently, they argued that the selection effect of OBA is stronger.

The present study suggests that this discrepancy may arise because experiments using the same feature dimension of different objects as cues utilized different types of object-based cues under low-load stimulus conditions. Object-based retro-cues can be further divided into endogenous retro-cues (presented centrally, pointing to the target location) and exogenous retro-cues (presented directly at the target location). Research has found that exogenous retro-cues are more effective than endogenous ones at low loads (load of 2), whereas no significant difference exists at high loads (load of 4) [?, ?]. At the neural level, the advantage of exogenous cues stems from their ability to trigger earlier responses in the prefrontal cortex (PFC) and faster top-down control signals from the PFC to the superior parietal lobule (SPL) and lateral occipital cortex (LOC). This implies that exogenous cues can more rapidly trigger brain regional activity and information transfer between regions [?], thereby exhibiting superior internal attentional selection effects.

Secondly, the quantity of retro-cues also exerts a complex influence on internal attentional selection. Setting multiple retro-cues to appear simultaneously or sequentially can alter the representational state of VWM and the allocation of attentional resources, thereby affecting the "fate" of both cued and non-cued items [?, ?]. The process of multiple retro-cues reveals the dynamic transitions between various states of VWM representations. [?] presented two retro-cues sequentially and found that the first cue places the cued item in a prioritized, protected, and stable state, while non-cued items enter a fragile state susceptible to interference or forgetting. When the second cue appears, some information in the fragile memory state can be enhanced and maintained through the orientation of internal attention, converting it into a relatively stable representational state; however, this stability remains inferior to performance under single retro-cue conditions [?]. Electrophysiological studies further validate this process: during sequential retro-cues, dynamic changes in alpha power reflect the prioritized allocation and regulation of attentional resources toward cued items, directly influencing the resources obtained by each memory item and strengthening internal attentional selection [?]. Even when multiple retro-cues are presented simultaneously, alpha waves remain involved in regulating representational states and redistributing attentional resources [?]. Subsequently, ERP research showed that compared to neutral retro-cues, the peak differences in N1/P2a components are more significant when multiple retro-cues (2 or 3) are presented simultaneously, meaning individuals can more effectively utilize cue information to allocate more attentional resources to task-relevant content. Meanwhile, the amplitude of the Negative Slow Wave (NSW) shows the greatest negative deflection when three retro-cues are presented simultaneously, followed by two cues, and is smallest under the single-cue condition [?]. This indicates that the NSW is related to the number of items simultaneously focused on by internal attention in VWM: although total cognitive resource investment is higher under multiple retro-cue conditions, the resources allocated to each individual item are relatively fewer and lower than in the single retro-cue condition. This reflects a dynamic allocation mechanism of attentional resources across different quantities of retro-cues, which consequently leads to variations in the RCB.

3.4 外部干扰

During the maintenance phase of Visual Working Memory (VWM), memory representations are susceptible to damage from external interference. According to existing research, external interference can be categorized into perceptual interference and dual-task interference (Pan et al., 2024). These types of interference, when combined with different experimental settings such as memory load and cue multiplicity, exert varying effects on the Retro-Cue Benefit (RCB).

In current research, perceptual interference is most commonly presented in the form of masking, which guides attention in a bottom-up manner. Although this type of interference does not require the individual to actively deploy cognitive resources for processing, it often interacts with other factors to disrupt the processing and manipulation of information within VWM. Studies have found that under conditions of high memory load and short Stimulus Onset Asynchrony (SOA), perceptual interference significantly weakens the RCB for dimension-based retro-cues (Liu et al., 2023). In such cases, individuals not only lack sufficient time to utilize retro-cues for attentional allocation, but the high memory load further exacerbates the demand for limited attentional resources. This intensifies resource competition and makes effective allocation and maintenance difficult, leading to a significant decline in RCB. Notably, the disruption of stable internal attentional maintenance by perceptual interference is not limited to high-load conditions. Even with low loads and sufficient SOAs, perceptual interference still weakens the RCB under orientation-based retro-cues (Liu et al., 2023). Furthermore, the impact of perceptual interference on RCB varies depending on the number of retro-cues. For instance, research observing β-band activity found that while multiple retro-cues can resist interference to ensure internal attentional selection, the suppression of β power only appears after the presentation of the memory probe. In contrast, under single retro-cue conditions, β power suppression is initiated before the probe appears (Schneider, Barth, & Wascher, 2017). This suggests that in the presence of perceptual interference, a single retro-cue can trigger response planning earlier than multiple cues, and its effect on enhancing memory performance is significantly superior to that of multiple cues. Additionally, perceptual interference can manifest as extra visual distractors presented alongside the retro-cue. Ye et al. (2020) used the color wheel (intended for the probe stage) as an additional visual distractor by displaying it simultaneously with the retro-cue and found that perceptual interference accompanying the cue weakens the RCB.

On one hand, this occurs because the simultaneous presentation of perceptual interference and retro-cues leads to competition for attentional resources, making it difficult for individuals to effectively focus on the retro-cue and reducing its utilization efficiency. On the other hand, the premature appearance of stimuli related to the probe stage triggers decision-making processes too early, interfering with the normal accumulation of decision information and the processing of the retro-cue, ultimately resulting in a reduced RCB.

In contrast, dual-task interference involves top-down attentional control and the reallocation of cognitive resources, which interrupts the memory task and affects the efficacy of internal attentional selection. Common cognitive interruption tasks include visual search tasks (Hollingworth & Maxcey-Richard, 2013), visual categorization tasks (Rerko et al., 2014), and parity judgment tasks (Makovski & Pertzov, 2015). In a study on object-based retro-cues using three arrows with random orientations as stimuli, Makovski and Pertzov (2015) found that while interruption tasks lead to impaired VWM representations, the RCB can mitigate this damage. This finding supports the view that dual-task interference does not diminish the RCB for object-based retro-cues (Makovski & Pertzov, 2015; Rerko et al., 2014). However, in dimension-based retro-cue tasks, dual-task interference does affect the selection of specific feature-dimension information by internal attention, which may be related to processing differences between different feature dimensions in memory and attentional allocation. Research using multi-feature stimuli with both color and orientation dimensions found that color features are sensitive to cognitive interruption during the prioritized maintenance phase of the retro-cue, making them susceptible to interference that hinders the generation of the RCB. Conversely, while orientation features better resist cognitive interruption during that phase, they are more easily disrupted during the attentional deployment phase (Liu et al., 2023). Furthermore, Zickerick et al. (2021) compared internal attentional selection under a high-demand arithmetic task and a low-demand number comparison task in a dimension-based retro-cue study. The results showed that under high-demand interruption, θ power in the Middle Frontal Gyrus (MFG) following the retro-cue was significantly lower than in the low-demand condition, indicating that high-demand tasks severely deplete attentional resources and weaken selection efficiency. Additionally, compared to a no-interruption condition, both types of interruption tasks led to weakened α-band suppression in posterior (parieto-occipital) regions after the retro-cue, suggesting impairment in the directional

Figure 1

Figure 1: Figure 1

Figure 1

Figure 2: Figure 1

selection and prioritized processing of target representations in VWM. Further analysis revealed that under high-demand interruption, posterior α lateralization—reflecting the redirection of internal attention for the primary task—was initiated before the interruption task was completed, showing temporal overlap with the processing of the secondary task. In the low-demand condition, these two processes were temporally dissociated. This indicates that high-demand interruption tasks interfere with the orderly transfer of attention from the distractor task back to the primary VWM task, exacerbating the impairment of representational information retrieval.

In summary, the RCB is jointly regulated by these four categories of factors, which interact in complex ways to form a multi-dimensional influence structure for internal attentional selection advantages.

4 总结与展望

In summary, the emergence of the internal attentional selection advantage in visual working memory (VWM) is the result of the synergistic interaction of multiple factors, each of which is closely linked to specific cognitive mechanisms. Centered on the cognitive mechanisms underlying the Retro-cue Benefit (RCB), this study systematically integrates key influencing variables to construct a cognitive model of internal attentional selection in VWM (see

), forming a theoretical framework based on the interaction between mechanisms and factors.

The model identifies three core mechanisms underlying the RCB: insufficient memory consolidation, stable sustained attention, and high-quality decision information. Retro-cues optimize the RCB through dynamic modulation of these three components.

Cognitive model of internal attentional selection in VWM. Note: (1) Orange circles represent the core mechanisms of the RCB, with their primary influencing factors labeled on the periphery; (2) Blue circles represent key factors and sub-factors affecting the RCB; (3) Unidirectional arrows indicate directional influence, while bidirectional arrows indicate reciprocal interactions.

First, the sufficiency of consolidation is a prerequisite for the effectiveness of retro-cues. By transforming transient visual signals into stable VWM representations, consolidation establishes the "baseline state" for subsequent internal attentional selection. Only when memory representations are not fully consolidated can retro-cues enhance the priority of target representations through orientation and selection. The sufficiency of memory consolidation is regulated by multiple factors, including the timing of internal attentional selection, the characteristics and load of memory items, and the type of cue. Specifically, the duration of the consolidation time (CT) determines the sufficiency of consolidation, while the cue-target interval (CTI) influences the continuation of the consolidation process to some extent, thereby affecting the efficacy of internal attentional selection. Regarding memory load, a serial processing mode of memory consolidation results in the depletion of consolidation resources for individual items as load increases; in a parallel processing mode, increased load affects CT by altering the available presentation time for each item. Furthermore, the complexity of memory item features and the selection of objects or features by different types of retro-cues also modulate the mode and speed of VWM consolidation.

Second, sustained attention is a necessary condition for the internal attentional selection advantage. It not only supports early attentional orientation and resource allocation but also dynamically differentiates the processing priority of memory items during the VWM maintenance phase. This ensures the stable activation of target representations while maintaining a degree of accessibility for non-target representations, thereby supporting the emergence of the internal attentional selection advantage. The modulation of sustained attention is influenced by retro-cue types, external interference, and the stimulus onset asynchrony (SOA). Object-based or feature-based retro-cues differ in their reliance on sustained attention due to variations in attentional allocation and the complexity of representational regulation. External interference increases the demand for sustained attention by competing for attentional resources, disrupting stable maintenance, or interrupting cognitive processing; the intensity of this demand varies with the type of interference and the SOA. In particular, the length of the SOA alters the protective efficacy of the retro-cue for the target representation, which in turn regulates the demand for sustained attention during the internal attentional selection process.

Third, decision information is the critical determinant of behavioral performance. The accumulation of high-quality information can accelerate the integration of decision evidence, shorten response times, and improve accuracy, directly facilitating the manifestation of the internal attentional selection advantage. This process is primarily regulated by memory load, external interference, and the number of retro-cues. An increase in memory load intensifies internal interference, reducing the quality of decision information and prolonging the retrieval time of target representations. External interference consumes attentional resources, interferes with information accumulation, or disrupts the stable attentional state required for sensory-motor mapping, thereby impairing the processing of decision information. Additionally, there is an interaction between the number of retro-cues and external interference; different numbers of cues lead to different onset timings for response planning, resulting in variations in their ability to protect the decision information accumulation process from interference.

Finally, the interaction between various influencing factors also acts upon the three core mechanisms mentioned above, affecting the efficacy of internal attentional selection. Among all factors, the retro-cue serves as the key tool for guiding internal attention to select VWM information; both its type and quantity exert varying degrees of influence on the three core mechanisms. Diverging from traditional research that examines influencing factors in isolation, this model uses the cognitive mechanisms of the RCB as an anchor to systematically organize and establish the relational paths between core mechanisms and various factors, providing theoretical support for understanding the operational mechanisms of internal attention in VWM.

From a neuroscientific perspective, internal attentional selection in VWM relies on neural modulation pathways formed by the coordination of multiple brain regions, with the occipital visual cortex, posterior parietal cortex (PPC), prefrontal cortex (PFC), and corticostriatal circuits serving as the core neural substrates. The occipital visual cortex is responsible for the storage and maintenance of short-term representations, and its neural activity is dynamically adjusted during the internal attentional selection process to lay the foundation for the prioritized processing of target representations [**?**]. As a hub of the top-down attentional control network, the PPC can prioritize memory representations based on task demands and bring relevant representations into the focus of attention. Simultaneously, the PFC maintains tight functional coupling with the visual cortex, receiving and temporarily storing prioritized representational information to stabilize the current selection state and organize subsequent processing [**?**]. Building on this, the corticostriatal circuit functions as an "output gate," filtering behaviorally relevant information and controlling output under the modulation of internal attentional selection [**?**]. Overall, through the temporal coupling, functional complementarity, and dynamic interaction of these brain regions, the internal attentional selection advantage in VWM is produced. By synthesizing cognitive and neural evidence, the retro-cue paradigm transcends the limitations of previous research that simply attributed VWM performance to encoding and storage capacities, revealing instead how unique cognitive regulatory mechanisms operate during the maintenance phase. This regulatory process does not achieve information gain by adding new representations; rather, it relies on the optimization of internal attentional selection to enhance the quality of existing representations, effectively mitigating the degradation of representational precision and the decline in memory accuracy common in traditional memory tasks. Furthermore, retro-cues challenge the traditional view of VWM representations as static, demonstrating that the manipulation of internal attention can trigger the dynamic reorganization and updating of representations, providing key evidence for the flexibility of internal information management in VWM. Although the retro-cue paradigm has provided a unique perspective and yielded significant results in understanding the impact of internal attention on VWM, many aspects still require further in-depth exploration.

4.1 基于主动抑制探寻内部注意选择假说的边界与冲突

In the field of Visual Working Memory (VWM), research on internal attentional selection based on continuous resource models has fully demonstrated the capacity for flexible allocation of attentional resources across different representations. However, derived theories—such as the removal hypothesis, the enhancement hypothesis, and the protection-from-interference hypothesis—remain divided regarding their explanations of the underlying mechanisms. The core controversy focuses on the processing of task-irrelevant information. Recent studies have proposed that individuals can utilize retro-cues to actively inhibit task-irrelevant information. This raises a critical question: is the weakening of task-irrelevant information in VWM the result of regulatory active inhibition or the passive decay of irrelevant information?

It is important to emphasize that active inhibition and resource allocation are not necessarily competing or mutually exclusive mechanisms; rather, they likely function as complementary dual-regulatory systems. While the continuous resource model emphasizes strengthening target representations and relatively weakening irrelevant ones by allocating more of the limited resources to the targets, active inhibition builds upon this by actively suppressing irrelevant representations through the activation of the right dorsolateral prefrontal cortex (DLPFC). Gao et al. (2023) employed a retro-cue paradigm comparing "remember" and "forget" retro-cue conditions. They found no significant difference between the two conditions in the parietal P3 component, which reflects the selective rehearsal and encoding of information, suggesting that the level of resource investment in task-relevant representations was comparable across both conditions. However, compared to the "remember" condition, the late positive potential (LPP) in the frontal lobe—which reflects active inhibition—was significantly enhanced in the "forget" condition. Furthermore, the LPP demonstrated a significant temporal predictive relationship with the parietal P3. These results indicate that the weakening of irrelevant representations under "forget" retro-cue conditions depends on active inhibition. Consequently, it can be further inferred that the inhibition of irrelevant representations by internal attentional selection in VWM does not stem solely from resource reallocation; when task-relevant information has already received a certain level of resource investment, the advantage of internal attentional selection may be enhanced through the active inhibition of irrelevant information processing.

Thus, the limitations of existing theoretical hypotheses may stem from an insufficient consideration of the active inhibition mediated by retro-cues. For instance, the removal hypothesis emphasizes the complete removal of irrelevant information from VWM, yet phenomena have been observed where non-target items are not entirely removed under low-reliability retro-cue conditions [**?**, **?**]. Similarly, the enhancement hypothesis highlights an increase in the weight of resource allocation for task-relevant items, but it struggles to explain cases where a Retro-Cue Benefit (RCB) is still observed even when resource allocation to task-relevant information remains unchanged under "forget" retro-cue conditions

[?, ?]. Therefore, can the divergences and conflicts among these hypotheses be reasonably resolved by investigating the synergistic mechanisms of resource allocation and active inhibition? Future research could further verify the interaction patterns and regulatory pathways between these two processes to refine the theoretical framework of internal attentional selection, providing new empirical evidence to resolve the mechanistic controversies within the field.

4.2 探究复杂刺激下内部注意选择效果的神经调控机制与生态效度优化的路径

Classic studies on internal attentional selection have predominantly utilized low-dimensional, simple stimuli, such as colored squares or tilted line segments, as experimental materials. However, in real-world scenarios, complex stimuli—such as faces, emotional images, and natural scenes—differ significantly in their representational formats and cognitive resource requirements. These differences impose higher demands on the investigation of the cognitive and neural mechanisms underlying internal attentional selection.

Lepsien et al. (2011) used faces and scenes as memory items and found that retro-cues specifically enhanced activation in category-sensitive cortical areas (e.g., the fusiform gyrus for faces and the parahippocampal gyrus for scenes). Simultaneously, functional connectivity between the dorsolateral prefrontal cortex (DLPFC) and these category-sensitive regions was significantly strengthened, with the connectivity strength positively correlating with memory precision. This suggests that the internal attentional selection of complex stimuli relies not only on resource allocation within the frontoparietal network but also on the enhancement of functional connectivity between the frontoparietal network and category-sensitive cortices. Subsequent studies have similarly confirmed that internal selection under complex stimulus conditions depends on a multi-pathway collaborative regulatory mechanism. Furthermore, research has revealed that priority processing triggered by retro-cues exhibits functionally differentiated representational characteristics across different brain regions: the Ventral Visual Stream (VVS) forms category-specific representations during the encoding phase that include sensory and semantic associations, which are maintained and selectively reproduced during the maintenance phase. In contrast, while the prefrontal cortex (PFC) exhibits category representations during encoding, the presentation of a retro-cue transforms task-relevant information into a more abstract, task-optimized representational format (Pacheco-Estefan et al., 2024). These findings provide critical neural evidence for understanding how internal attention flexibly adapts to behavioral demands in realistic contexts. Additionally, internal attentional selection using real-world scenes exhibits hierarchical processing characteristics. Kuo et al. (2018) found that retro-cues reinforce the hierarchical representational processing between scenes and objects by enhancing functional connectivity between the frontoparietal network and the ventral temporal lobe (VTL). Early visual cortices process scene layout information, while the VTL focuses on processing detailed object information. When a retro-cue points to a threatening object within a scene (e.g., a knife), the functional connectivity between the frontoparietal network and the VTL is significantly enhanced. When a semantic association exists between the scene and the object (e.g., kitchen-knife), the retro-cue benefit (RCB) is significantly increased, and this effect correlates significantly with the activation intensity of the middle temporal gyrus (a region associated with semantic encoding). These results indicate that internal attentional selection in real-world scenes undergoes a hierarchical process involving semantic integration, sub-scene filtering, and target feature activation, requiring the coordination of multiple brain regions. This aligns closely with the logic of human cognition, which prioritizes understanding the meaning of a scene before focusing on key information.

The aforementioned studies highlight the limitations of using simple stimuli. First, such stimuli have low requirements for feature integration and thus fail to reflect the dynamic cognitive processes—involving multi-feature binding, semantic encoding, and memory maintenance—inherent in real-world scenes. Second, they lack ecological validity, making it difficult to directly generalize the revealed internal attention mechanisms to memory and attention tasks in daily life. Future research should explore the mechanisms of internal attention using complex or real-world stimuli. Researchers could leverage technologies such as artificial intelligence and virtual reality to construct immersive real-world scenes, thereby enhancing the ecological validity of their studies. Furthermore, cross-species research, such as single-cell recording in macaques, could be conducted to reveal the neural coding mechanisms of internal attentional selection under complex stimulus conditions, providing deeper insights into the comprehensive understanding of complex human cognitive processes.

4.3 扩展对神经发育障碍群体内部注意选择的机制差异与潜在限制的探究

Current research on internal attentional selection in typically developing (TD) populations is relatively extensive. However, studies involving neurodevelopmental disorders remain limited, with research primarily focused on Attention-Deficit/Hyperactivity Disorder (ADHD). Using a retro-cue paradigm, Superbia-Guimarães et al. (2022) found that children with ADHD exhibited a higher Retro-cue Benefit (RCB) under valid retro-cue conditions compared to neutral conditions. This performance was comparable to that of TD children, leading the authors to suggest that individuals with ADHD do not lack the capacity for internal attentional selection. Nevertheless, the cognitive demands of the Visual Working Memory (VWM) task in that study were relatively low. While it demonstrates that children with ADHD can utilize retro-cues to orient toward targets in simple color recognition tasks, it does not rule out potential deficits in internal attentional selection under conditions involving inhibitory control or high memory loads. Other neurophysiological evidence reveals a more complex picture. Luo et al. (2019) found that in spatial VWM tasks, the amplitudes of both N2pc and CDA components were significantly weaker in individuals with ADHD than in the control group. This intergroup difference became more pronounced as memory load increased, suggesting that individuals with ADHD have deficits in attentional selection and memory maintenance, and that these capacity limitations are particularly evident when resource competition intensifies. Furthermore, research has indicated that individuals with ADHD exhibit activation deficits in the bilateral prefrontal cortex (PFC) during VWM inhibitory control tasks, accompanied by under-activation in multiple regions of the parietal and temporal lobes during response inhibition tasks. This implies potential functional abnormalities in the core neural circuits underlying internal attentional selection in the ADHD population (Hou et al., 2023). Consequently, future research should systematically verify the internal attentional selection capabilities of the ADHD population by manipulating key variables such as task difficulty, memory load, and interference intensity within retro-cue paradigms and their variants.

Beyond ADHD, the internal attentional selection capabilities of other neurodevelopmental disorder populations also warrant attention. Research on individuals with Learning Difficulties (LD) generally indicates the presence of executive function deficits, particularly manifested as insufficiencies in inhibitory control and VWM regulation. These deficits make them more susceptible to the influence of distracting information during cognitive processing (Capodieci et al., 2023).

Given that the generation of the RCB relies on a dynamic process of inhibiting irrelevant information and strengthening target representations, such deficits are likely to limit the internal attentional capacity of the LD population. Similar phenomena are observed in individuals with Autism Spectrum Disorder (ASD), who commonly exhibit abnormalities in the activation and functional connectivity of the frontoparietal network (Yuk et al., 2020). Behavioral studies have also found that individuals with ASD face significant difficulties in using external social cues (such as gaze direction or facial orientation) for attentional orientation (Wang et al., 2022). Although these findings primarily concern external attention mechanisms, they raise a critical question: when internal attentional selection processes depend on similar social cues, do individuals with ASD face the same processing constraints? In summary, conducting research on internal attention within neurodevelopmental disorder populations not only helps reveal the specific cognitive and neural mechanisms and potential limitations of different disorder types at the level of internal attentional processing but also provides empirical evidence for refining the theoretical framework of internal attention.

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Retro-cue costs and benefits in a double-cueing paradigm suggest multiple states in visual short-term memory.

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Keywords: visual working memory, internal attention, internal-attention advantage, retro-cue, retro-cue paradigm