# Sequentiality in Cognitive Control and Its Neural Mechanisms

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## Abstract

Cognitive control constitutes the dynamic regulatory mechanism through which individuals implement goal-directed behavior. Traditional cognitive control research has focused on comparisons between discrete cognitive control states; however, behaviors dominated by cognitive control in reality often exhibit sequentiality, requiring maintenance of goal consistency and flexible updating across multiple steps. This article systematically reviews research advances on the behavioral, computational, and neural mechanisms of cognitive control from a sequential perspective, identifies a convergence between cognitive control research and sequential memory research, and points out that the sequential nature of cognitive control represents a cross-disciplinary domain worthy of in-depth exploration. Future research should emphasize promoting theoretical integration and paradigm innovation between cognitive control and sequential representation, and explore its practical application value.

## Full Text

## The Sequential Nature of Cognitive Control and Its Neurocognitive Mechanisms

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**Abstract:** Cognitive control functions as a dynamic regulatory mechanism that enables individuals to achieve goal-directed behaviors. Although traditional research has largely emphasized comparisons between discrete control states, real-world control-driven behaviors are inherently sequential, requiring the preservation of goal consistency and the capacity for flexible updating across multiple steps. Here, we systematically review behavioral, computational, and neural investigations of cognitive control from a sequential perspective, and highlight a notable convergence between studies of cognitive control and serial memory. We propose that the sequential nature of cognitive control is a critical interdisciplinary frontier. Future directions should focus on integrating theories of cognitive control with sequence representation, developing novel experimental paradigms, and examining the practical implications of this framework.

**Keywords:** Cognitive control; Sequential processing; Representation; Abstract task; Memory

Cognitive control, also known as executive function, refers to the psychological process through which individuals mobilize cognitive resources in a top-down manner according to task goals, selectively processing, planning, storing, and manipulating information to achieve dynamic regulation of thought and behavior (Friedman & Robbins, 2022; Menon & D' Esposito, 2022; Miller & Cohen, 2001; Yang et al., 2019). This process involves not only multiple interacting subprocesses such as decision-making, working memory, goal planning, attention regulation, and metacognition, but also requires individuals to promptly inhibit automatic responses that may deviate from the intended goals (Badre, 2025; Botvinick et al., 2004; Ritz et al., 2022).

Many classic experimental paradigms in cognitive control research have focused on comparisons between discrete cognitive control states. In the Stroop task, for example, participants must report the ink color of color words. When the word meaning and ink color are congruent, cognitive control demands are low; when they are incongruent, stronger cognitive control is required to suppress automatic word processing, resulting in slower responses and higher error rates. This demonstrates a cognitive control difference between congruent and incongruent conditions (Czernochowski, 2015; Di Russo & Bianco, 2023). However, goal-directed behaviors in real life do not involve random alternation between discrete states; rather, they exhibit a high degree of sequentiality (Frölich et al., 2022), requiring the maintenance of internal goal consistency and flexible updating across multiple steps (Desrochers et al., 2015; Hommel, 2022). For instance, cooking a dish requires sequentially completing steps such as washing and chopping ingredients, heating, seasoning, and plating, with each stage depending on the completion of the previous step and the maintenance of current goals (Doyle et al., 2025). This indicates that cognitive control has temporal span and sequence dependence, and focusing solely on single time points cannot reveal its complete mechanisms. Therefore, expanding the research perspective from "discrete states" to "sequential processing" is essential for uncovering the dynamic mechanisms underlying sequence processing (Desrochers et al., 2022).

Furthermore, research on the sequential nature of cognitive control aligns with the developmental trajectory of the sequence processing field itself. In recent years, the objects of study in sequence processing have expanded from concrete stimulus sequences to abstract sequences. Concrete stimulus sequence processing primarily refers to the memory encoding and retrieval of perceptual inputs with clear physical attributes (such as numbers, letters, tones, rhythms, etc.). Such sequences form the basis of cognitive functions like language comprehension and music perception, and previous research has extensively explored concrete stimulus sequences, revealing multiple forms of sequential memory representation mechanisms (Dehaene et al., 2015; Hurlstone et al., 2014; Mongillo & Tsodyks, 2025; Oberauer & Lewandowsky, 2008). However, whether these mechanisms equally apply to abstract sequence information remains to be explored. Compared to concrete information sequences, abstract information sequences are characterized by their independence from specific stimuli and their capacity to generalize across different contexts (Bellet et al., 2024; Cole, Reynolds, et al., 2013; Desrochers et al., 2022). For example, a particular cognitive control state may apply to different stimuli within a task, whereas stimulus-specific processing mechanisms cannot easily generalize to other stimuli. Therefore, cognitive control state sequences constitute a form of abstract sequence. Based on this, investigating the memory representation of cognitive control sequences can test the breadth of applicability of sequence representation mechanisms and help deepen our understanding of sequence representation itself.

## 2 Research Progress on Sequential Cognitive Control

The sequential nature of cognitive control can be categorized based on sequence length into short-sequence effects based on instantaneous adjustment and long-sequence effects based on sustained expectation (Y. Lee et al., 2025). Currently, short-sequence effects have gradually become a research hotspot, typically involving adaptive adjustments between adjacent trials. For example, the conflict level of the previous trial (Bognar et al., 2024) or task performance (P.-S. Lee et al., 2025) can influence response times and accuracy in the current trial. In contrast, long-sequence effects focus on sequences spanning three or more trials, potentially reflecting cumulative effects of cognitive control or memory integration processes (Brown & Koch, 2024; Farooqui et al., 2023), though research in this area has lagged due to the complexity of experimental design.

### 2.1.1 Common Short-Sequence Effects in Cognitive Control

In conflict tasks (such as the Stroop task), performance on the current trial is influenced by the conflict level of the previous trial: if the previous trial was a high-conflict (incongruent) condition, the current incongruent trial shows faster responses and lower error rates. This phenomenon is known as the congruency sequence effect (CSE) (Braem et al., 2019; Egner, 2007; Gratton et al., 1992). CSE is often accompanied by bottom-up sequence learning effects, such as stimulus-response feature integration. However, through experimental designs that minimize confounding factors, researchers can observe high-level cognitive control sequence effects independent of low-level mechanisms (Braem et al., 2019; Y. Lee et al., 2025). This control-specific sequence effect is also termed the conflict adaptation effect (Egner & Hirsch, 2005; Kerns et al., 2004), reflecting rapid adaptive adjustments of cognitive control across contexts: incongruency in the previous trial triggers conflict monitoring processes, thereby enhancing control resource allocation in subsequent trials and significantly reducing incongruency effects (such as increased reaction times or error rates), ultimately optimizing behavioral performance (Fu et al., 2022).

Post-error slowing (PES) refers to the phenomenon where individuals exhibit significantly longer response times following an error, thereby reducing the likelihood of subsequent errors. PES is generally considered a dynamic response mechanism of the cognitive control system to error signals, which monitors error occurrence and temporarily reallocates control resources (such as increasing caution or adjusting decision thresholds) to optimize subsequent behavioral performance (Danielmeier & Ullsperger, 2011; Fievez et al., 2022; Schroder et al., 2020). PES is consistently observed in both conflict tasks (Cravet & Ger, 2026; Danielmeier et al., 2011; Derrfuss et al., 2022) and non-conflict tasks (de Mooij et al., 2022; Kirschner et al., 2021). Neuroimaging studies have shown that error commission significantly enhances activity in the posterior medial frontal cortex (pMFC), which supports attentional focusing and motor inhibition through functional connectivity with visual and motor regions, thereby implementing top-down regulation to ensure performance optimization and reduce error repetition (Danielmeier et al., 2011). Single-neuron recordings have further revealed the microscale neural mechanisms underlying error self-monitoring and behavioral adjustment associated with the pMFC (Fu et al., 2022; Fu et al., 2023; Fu et al., 2019).

Sequence effects triggered by task type switching are primarily manifested as switching costs: compared to task repetition, task-switching conditions show significantly prolonged reaction times and decreased accuracy (Egner, 2023; Kiesel et al., 2010). Switching costs reflect the sequential dependence of cognitive control, wherein repeated sequences are easier to execute while switching requires additional cognitive effort. One theory posits that switching costs arise from task-set inertia, whereby after executing a specific task, the cognitive system tends to maintain activation of that task set, expecting subsequent tasks to be of the same type, thus requiring the overcoming of this residual activation during switching (Allport et al., 1994). Another theory emphasizes the task-set reconfiguration process: switching necessitates actively configuring a new set of cognitive operations, whereas repetition requires no additional reconfiguration, thereby reducing resource consumption (Rogers & Monsell, 1995). The expected control value theory further incorporates switching costs into a broader cognitive resource allocation mechanism, emphasizing that individuals allocate limited cognitive resources based on cost-benefit trade-offs during task switching, providing a more macroscopic explanation for switching costs (Frömer et al., 2021).

### 2.1.2 Order Dependencies in Short-Sequence Effects

In cognitive control research, short-sequence effects typically focus on interactions between adjacent trials rather than differences in the overall order of experimental conditions. For example, in task switching, switching costs remain stable regardless of whether the switch is from Task A to Task B or from Task

B to Task A. Therefore, such sequence effects are more accurately described as "sequence-dependent effects" rather than "order effects" in the strict sense. However, the dynamic adjustment of cognitive control is influenced by the directional order of control states. In congruency sequence effects, for instance, sequences transitioning from incongruent to congruent versus from congruent to incongruent often show asymmetry: the former reduces subsequent interference due to residual high control levels, while the latter incurs greater costs because conflict is re-encountered in a relaxed state (Bognar et al., 2024; Egner, 2023). Asymmetric effects also appear in task switching, known as asymmetric switch costs: switching from a non-dominant task (such as a second language requiring more cognitive control) to a dominant task (such as a highly automated native language) exhibits higher switching costs due to inhibitory residues, requiring additional control resources compared to the reverse direction (Eckart et al., 2023; Gade et al., 2021; Zhou et al., 2024).

These findings challenge the assumption in classic experimental paradigms that treats cognitive control as "state-independent." Individuals' regulation of control states depends not only on the characteristics of current stimuli but also on multiple factors including task context (Alzahabi et al., 2022; Xiao et al., 2023), prior experience (Jiang et al., 2014; Yanaoka et al., 2024), and predictions about future task structure (Desrochers et al., 2019; Masís Obando et al., 2025). Neglecting the influence of these factors during task execution may lead to underestimation of the dynamic characteristics and regulatory mechanisms of cognitive control along the temporal dimension. More importantly, compared to single cognitive control states, cognitive control sequences can more accurately reflect complex behaviors in real life.

### 2.1.3 Long-Term Memory Effects of Short Sequences

Although most research has focused on short-term effects between adjacent trials, sequential dependence in cognitive control is not limited to this scope. Evidence indicates that conflict adaptation effects can span longer inter-trial intervals. The conflict status from two trials back (N-2) also modulates performance on the current trial: similar to the classic congruency sequence effect, when trial N-2 is incongruent, the congruency effect on trial N is significantly reduced compared to when trial N-2 is congruent (Akçay & Hazeltine, 2008; Lim & Cho, 2021).

Generally, congruency sequence effects weaken or even disappear as the inter-trial interval increases (Egner et al., 2010). However, recent studies have shown that cognitive control can exhibit memory effects over longer time spans, guiding current task performance through long-term memory retrieval of prior experiences (Brosowsky & Crump, 2018; Schiltenwolf et al., 2024). For example, when the same stimulus repeats across distant trials, the congruency condition from the previous trial becomes bound with that stimulus in episodic memory, influencing behavioral performance in subsequent trials. Specifically, if a stimulus first appears in an incongruent condition, its congruency effect is significantly reduced when it reappears (Brosowsky & Crump, 2018). In summary, the dynamic characteristics of cognitive control are manifested not only in immediate adjustments between adjacent trials but also in forming lasting influences on subsequent performance through long-term memory.

## 2.2 Research on Long Sequences in Cognitive Control

Compared to short-sequence effects, research on long sequences is relatively scarce, primarily focusing on task sequences, though some studies have attempted to examine long-sequence effects composed of other types of cognitive control states. Given the unique value of long-sequence research in revealing the persistence and hierarchical nature of cognitive control, interest in this direction has gradually increased in recent years.

### 2.2.1 Task Long Sequences

To understand how individuals process complex long sequences, researchers can employ extended task sequence designs to examine hierarchical integration of abstract rules, goal maintenance, and information regulation across time (Schneider & Logan, 2006). In task-switching paradigms, if switching patterns (such as A-B-B-A) repeat, individuals may form high-level sequence representations independent of single tasks. Studies have found that when switching between two long task sequences, reaction times for the first trial after the switch are significantly prolonged, manifesting as a sequence initialization cost effect, suggesting that task processing depends on sequence-level representations (Schneider & Logan, 2006).

Using the task long-sequence paradigm, research has found that activation in the rostrolateral prefrontal cortex (RLPFC) gradually increases as the sequence progresses, indicating that this brain region can monitor the current position within a sequence in real time (Desrochers et al., 2015; Desrochers et al., 2019). Additionally, after completing long-sequence tasks with certain switching regularities, the hippocampus rapidly replays the task sequence during post-task rest states, demonstrating that long task sequences can be encoded into memory (Schuck & Niv, 2019).

### 2.2.2 Long-Sequence Research on Other Types of Cognitive Control

Although research on the encoding mechanisms of longer congruency sequences remains limited, studies have begun to examine how consecutive congruent trials influence subsequent trials. One hypothesis suggests that when two identical trial types appear consecutively, people tend to predict that the next trial will be different—the "gambler' s fallacy" effect (Jarvik, 1951). However, experimental results show that sequences of congruent conditions do not produce the expected gambler' s fallacy effect; instead, congruency sequence effects demonstrate cumulative characteristics across trials, whereby the congruency effect on the current trial weakens when previous trials are consecutively incongruent, and this reduction further declines as the number of consecutive incongruent trials increases (D' Angelo et al., 2013; Jiménez & Méndez, 2014).

Similarly, research using the Go/NoGo paradigm has examined long-sequence effects (N=3), revealing that sequence trials are a key factor modulating behavioral responses and electrophysiological activity. When stimulus sequences violate expectations established by previous trials (such as when a continuous pattern is interrupted, i.e., AAB or ABB), both Go and NoGo trials elicit slower behavioral responses and higher error rates. Additionally, expectancy-violating trials evoke larger N2 and P3 amplitudes (Smith et al., 2010). This violation effect is closely related to sequence length, with stronger changes in behavioral performance and EEG indices as the number of repetitions of the preceding pattern increases (Thomas et al., 2009). These results demonstrate that subjective expectations formed during sequential trials can systematically influence cognitive processing.

## 3.1 Encoding Mechanisms of Sequence Processing

Learning, memory, and recall of sequences fundamentally depend on the brain' s effective encoding and representation of sequences. For a considerable period, research in this field primarily relied on sequences constructed from concrete sensory stimuli (such as letters, musical notes, spatial locations). The experimental tractability of these materials enabled researchers to identify and validate several core principles of sequence representation. Studies have shown that neural representations of sequences depend not only on the processing of individual elements but also on the encoding of the sequence as a whole (gestalt coding) (Conen & Desrochers, 2022). A crucial characteristic of this holistic representation is its specificity to different sequences. For example, sequence-specific neurons have been identified in the motor cortex of non-human primates, which show selective activation only for specific action sequences and no response to sequences containing the same elements in different orders, indicating that sequences can be represented in a holistic form (Mushiake et al., 1991). One manifestation of holistic representation is the sequence replay mechanism, where neurons in brain regions such as the hippocampus spontaneously reactivate specific neural activity patterns formed during prior sequence processing during rest or non-task states (Kaefer et al., 2022; Liu et al., 2019).

Holistic representation may be constrained by short-term memory capacity when facing longer or more complex sequences, leading to chunking of sequences and specific encoding of partial information (Ding, 2025). Specifically, neural activity tracks not only the onset and offset boundaries of chunks but also assigns specific ordinal positions to each event within a chunk (Dehaene et al., 2015; Ding, 2025). In this context, one key mechanism is associative chaining, which encodes relationships between adjacent items such that when one item is retrieved, subsequent items are recursively activated and sequentially extracted (Caplan et al., 2022). Another mechanism is positional coding, which binds absolute or relative position markers to items in a sequence, using these markers as retrieval cues to ensure the order of sequence recall (Brown et al., 2000; Burgess & Hitch, 1999). When multiple sequences need to be encoded simultaneously, a competitive queuing mechanism often operates, where multiple candidate items in a parallel activation state compete to determine the final output order (Averbeck et al., 2003; Bullock, 2003; Grossberg, 1978). Additionally, during sequence recall, inhibiting already-executed or non-target responses can prevent repetition errors, thereby maintaining the accuracy of sequence output and ensuring the orderly execution of cognitive control (Henson, 1998; Vousden & Brown, 1998).

## 3.2 Abstract Sequence Processing and Abstraction in Sequence Processing

In sequence processing research, the level of abstraction in information representation is a critical factor influencing multitask adaptability and generalization capacity. Unlike concrete information sequences, abstract information sequences are independent of specific sensory stimuli and can encompass broader contexts, reflecting higher-level structural organization. Their encoding basis is not limited to sensory modalities but depends on task rules, transition patterns of cognitive states, and changes in behavioral goals. This structure-centered encoding approach endows abstract sequences with stronger context independence and transfer potential across tasks, thereby supporting efficient strategy integration and execution regulation in diverse cognitive environments (Cole, Laurent, et al., 2013; Desrochers et al., 2022). For example, when executing the task rule "determine whether the current stimulus repeats," individuals may be in the same cognitive control state—such as maintaining working memory load or preserving comparison strategies—regardless of whether they face visual shapes, color symbols, or auditory sequences (Chiu & Egner, 2019).

Similarly, in categorization tasks, the instruction sequence "first judge color, then judge shape" can be applied to any stimuli containing color and shape attributes without requiring reconstruction of the control strategy (Botvinick & Cohen, 2014). Because of these characteristics, Abstract Cognitive Task Sequences (ACTS) have been proposed in recent research as a concept deserving independent investigation (Desrochers et al., 2022).

In actual task switching or sequence learning, abstract sequences possess greater sequence compression capacity, meaning that even concrete sequences may be represented as more abstract ones. Sequence compression capacity refers to the system' s ability to integrate multiple low-level operations or states into higher-level abstract units when processing complex task sequences, thereby reducing information redundancy, enhancing processing efficiency, and supporting rapid reuse of control processes within complex task structures. For example, algebraic pattern representation, as a high-level mechanism of sequence processing, supports the extraction of structural regularities (such as AAB or ABA patterns) during processing, enabling rule learning and pattern generalization across sequences (Dehaene et al., 2015; Planton & Dehaene, 2021; Shima et al., 2007).

Abstract control sequences leverage their structural characteristics to demonstrate strong generalization potential and execution efficiency in cross-task applications (Cole, Reynolds, et al., 2013; Johnson et al., 2023). Additionally, this abstract sequence compression may be related to geometric reconfiguration mechanisms in neural representational space. For instance, recent research has introduced a two-dimensional neural geometry framework that "folds" linear sequences into two-dimensional neural space, where two orthogonal dimensions encode local ordering within chunks and global ordering across the entire sequence, respectively (Fan et al., 2025). This "folding" essentially constitutes dimensionality reduction and abstraction of control representations (Badre et al., 2021), allowing working memory to retain structural information while reducing interference and enhancing readability, thereby overcoming capacity limitations and efficiently representing longer sequences.

## 4 Sequence and Cognitive Control Research: Converging Paths

Traditional research on cognitive control sequences has primarily focused on processes such as task switching and short congruency sequences, with relatively insufficient attention to long-sequence processing. Meanwhile, although sequence representation research has revealed basic principles of sequence learning and memory, it has less frequently delved into the mechanisms underlying abstract sequence processing. The intersection of these two domains—sequential representation in cognitive control—precisely fills this research gap. Integrating cognitive control with sequence representation can not only provide a more comprehensive explanation of human flexibility and efficiency in long-sequence tasks but also offer a new theoretical framework for understanding the neurocognitive mechanisms of abstract control sequences. We argue that this interdisciplinary domain possesses natural 合理性, as elaborated below.

### 4.1 Similarities Between Sequence Processing and Cognitive Control

Although sequence processing and cognitive control belong to two relatively independent research domains, the experimental phenomena they investigate share notable similarities, such as both involving "inhibition" processes. In the cognitive control domain, the N-2 repetition cost (N2RC) is widely observed in task-switching paradigms, where performance on the current task (trial N) is typically worse when it matches trial N-2 but differs from trial N-1 (i.e., an ABA sequence) compared to when all three are different (i.e., a CBA sequence). It is generally believed that to successfully execute the current task, the cognitive system must actively inhibit the previous task set to clear residual activation and avoid potential cognitive conflict (Mayr & Keele, 2000). In motor sequence learning, particularly when sequence rules change or stimulus-response mappings are reversed, the cognitive control system must inhibit inappropriate associations to prevent erroneous responses and support controlled processing (Verwey, 1999). In sequence recall tasks, after successfully retrieving an item, the cognitive system applies systematic inhibition to that item to prevent its repeated output in subsequent positions. This process similarly relies on inhibiting recently active but currently irrelevant mental representations to ensure sequence accuracy (Hurlstone et al., 2014). This cross-domain overlap of mechanisms not only reveals the universal role of inhibition in cognitive organization but also suggests theoretical integration potential between sequence processing and cognitive control.

### 4.2 Sequence Processing in Working Memory

As a core component of cognitive control, working memory exhibits intrinsic connections with sequence processing and demonstrates high mechanistic similarity. The core function of working memory lies in the active maintenance and manipulation of information, a process that often unfolds in sequence form. For example, in the n-back task, individuals must continuously monitor and update a dynamic stimulus sequence, with each new item requiring the cognitive system to sequentially adjust memory content and update context. This ordered maintenance of target information not only reflects the cognitive control properties of working memory but also represents a "progressive dynamic adjustment" mechanism of sequence processing (Cai et al., 2021; Huang et al., 2025). Additionally, experimental evidence indicates that the prefrontal cortex exhibits neural activity patterns that change systematically with sequence position in serial working memory tasks (Desrochers et al., 2015; Xie et al., 2022). This aligns with positional coding patterns in sequence recall tasks (Dehaene et al., 2015; Hurlstone et al., 2014), further suggesting that cognitive control and sequence representation may rely on common neurocomputational foundations for implementing ordered information representation and manipulation.

The sequences processed by working memory can encompass different levels of abstraction. Typically, working memory processes concrete stimulus sequences (such as letters, spatial locations, and other perceptual information); however, its content can also be abstract cognitive control states (such as task rules, intentional goals). When these cognitive control states are themselves organized according to logical or temporal order, they can form higher-order cognitive control sequences. Therefore, working memory may occupy a hub position between cognitive control and sequence representation: it both undertakes fundamental cognitive control functions to process underlying concrete stimulus sequences and participates in representing and regulating abstract cognitive control sequences.

### 4.3 The Coordinating Relationship Between Prefrontal Cortex and Hippocampus

The deep connection between cognitive control and sequence memory is manifested in the functional interactions between the prefrontal cortex (PFC) and the hippocampus. Traditionally, the prefrontal cortex has been viewed as the center for executive regulation, rule maintenance, and goal-directed behavior

(Miller & Cohen, 2001), while the hippocampus has been primarily responsible for encoding episodic memory and spatial sequences (Fortin et al., 2002; O' Keefe & Dostrovsky, 1971). However, recent research reveals that these two brain regions do not operate independently but rather achieve coordinated representation and flexible retrieval of information through dynamic coupling. First, studies have found that after rule learning, neural patterns in the prefrontal cortex are replayed in brief, synchronized sequences during slow-wave sleep and are highly coupled with hippocampal sharp-wave ripple events (Peyrache et al., 2009). Subsequently, during sharp-wave ripple events in the awake state, research has shown that activated prefrontal neurons tend to encode behavioral information related to hippocampal replay content, while suppressed neurons correspond to irrelevant representations (Jadhav et al., 2012). Furthermore, studies have revealed that in spatial alternation tasks, hippocampal reverse and forward replay reproduce past and future paths, respectively, in a serialized manner and synchronize with prefrontal activity, thereby enabling a dynamic shift from retrospective evaluation to prospective planning during learning (Shin et al., 2019).

Recent theories propose that the brain contains two parallel yet interconnected systems for representing abstract knowledge: a control system centered on the frontoparietal network (FPN) and a cognitive map system involving the medial temporal lobe (MTL, including the hippocampus), medial prefrontal cortex, and orbitomedial prefrontal cortex (OMPFC). Although both systems encode structured task information, their representational formats differ fundamentally: the MTL-OMPFC system organizes task experiences into flexible "cognitive maps" —spatialized or topological representations based on relational structures that support inference and path planning for unexperienced states—whereas the FPN transforms these structures into "production rules" —if-then conditional-action mappings that enable rapid decision-making and behavioral execution (Vaidya & Badre, 2022).

This theoretical distinction is supported by multiple neurophysiological studies. For example, research has found that both the hippocampus and prefrontal cortex encode task variables in high-dimensional space while simultaneously exhibiting cross-condition generalization capabilities and abstract representations of relationships among task variables—capturing task latent structures through constructing shared feature variables to support generalization. The hippocampus stably maintains abstract geometric structures during tasks, providing a coherent relational scaffold for events, whereas the geometric structure of the prefrontal cortex rapidly adjusts according to current circumstances, abstractly encoding context, value, and action before stimulus presentation and prioritizing the strengthening of immediate action and outcome representations afterward to meet the demands of rapid decision-making (Bernardi et al., 2020).

Dynamic interactions between the hippocampus and prefrontal cortex, such as theta-band synchronization (Jones & Wilson, 2005) and sharp-wave ripple-triggered neural sequence replay, may be key mechanisms for transforming "cognitive maps" into "control programs," enabling prefrontal cortex to call upon and compile sequence information stored in the hippocampus into flexible control strategies during offline or planning states. Thus, the prefrontal cortex and hippocampus support sequence memory representation and retrieval through close collaboration (Foster, 2017).

## 5.1 Theoretical Integration of Cognitive Control and Sequence Representation

Current mainstream theories of cognitive control are largely built upon discrete cognitive control states or short-term sequence adjustments, making it difficult to characterize how individuals maintain goal direction over long sequences and adjust control strategies in real time as the sequence progresses. Therefore, developing cognitive control theories applicable to long sequences is crucial, requiring deep integration of existing cognitive control theories with sequence representation theories. This integration can not only open new directions for cognitive control research but also help extend sequence representation theory to the level of cognitive function.

The key to achieving effective integration of cognitive control and sequence representation lies in treating cognitive control itself as a representable mental state. Previous research has often simplified cognitive control to unidimensional variations in strength (such as the amount of control resource allocation), overlooking its internal structure and diversity. However, recent studies have shown that different cognitive control states exhibit distinct activation patterns in the brain (Freund, 2024; Yang et al., 2024), and that cognitive control can be learned and remembered like concrete stimuli, dynamically adjusting the weighting of recent versus remote experiences according to environmental volatility (Egner, 2014; Jiang et al., 2014). These findings collectively suggest that cognitive control likely forms stable representations in memory systems, much like other concrete stimulus sequences.

## 5.2 Experimental Paradigm Innovation

Investigating the sequential processing mechanisms of cognitive control urgently requires experimental paradigm innovation. The task sequence paradigm has become an ideal starting point for exploring cognitive control sequence processing due to its operational simplicity and controllable parameters. For example, when participants are required to complete multiple task sequences, computational modeling results reveal the existence of multiple sequence representations that guide expectations for future tasks, providing direct evidence for multiple representation mechanisms of cognitive control sequences (Yang et al., 2024). Additionally, the task sequence paradigm can be used to examine sequence replay mechanisms—functional magnetic resonance imaging studies have found that the human hippocampus replays task-state sequences from previous tasks during rest periods, a process that may participate in memory consolidation and offline optimization of cognitive control sequences. Beyond task sequences, future research can further investigate representation mechanisms of other forms of cognitive control state sequences (Schuck & Niv, 2019). For example, by designing specific conflict sequence structures (such as "congruent-incongruent-incongruent-congruent" stimulus presentation patterns), researchers can systematically examine how cognitive control prospectively adjusts based on conflict regularities within sequences.

## 5.3 Application Value

Research on cognitive control sequences promises to provide theoretical and methodological foundations for modeling real-life sequential behaviors, thereby generating important application value in understanding complex task execution and goal-directed behavior. For example, task sequence research may have critical value for analyzing and treating mental disorders. Addiction behaviors, for instance, can be viewed as pathological sequences composed of sub-goals such as drug-seeking, drug-preparing, and drug-using. Due to weakened prefrontal control functions in addicts, they have difficulty flexibly adjusting this sequence, leading to compulsive cycles. Task sequence research provides new intervention approaches for this: repairing sequence control mechanisms through neuromodulation of brain regions that monitor sequence progression (such as RLPFC) or extinction therapy based on sequence structure to break addiction cycles (Desrochers & McKim, 2019). Additionally, task sequence research provides directions for assessment and intervention of other neurofunctional disorders (such as task execution deficits in patients with frontal lobe damage).

## 5.4 Implications of Cognitive Control Sequence Research for Brain-Inspired Intelligence

Humans organize sequential goal-directed behaviors along the temporal dimension, relying on structural maintenance in working memory, prefrontal allocation of control resources, expectancy-based monitoring mechanisms, and flexible responses to interference and goal switching. These abilities represent the core shortcomings of current artificial intelligence in achieving autonomy and adaptability in open environments. Although brain-inspired computing often focuses on simulating algorithms or network architectures, the true challenge lies in reproducing the sustained cognitive organization capabilities that humans demonstrate in complex, nested, non-stationary tasks. Research on cognitive control sequence representation provides biological constraints and functional implementation solutions for this: individuals rely on task-level representations, subgoal maintenance mechanisms, and error recovery strategies during procedural tasks, offering inspiration for constructing brain-inspired executive systems with dynamic regulatory capabilities. Current AI systems mostly depend on large-scale data training and exhibit excellent pattern recognition abilities on specific tasks, but their behavior is typically limited to "passive responses" to immediate inputs, lacking active construction and regulation of long-term goals

(Lake et al., 2017). Future brain-inspired systems need to transcend traditional stimulus-response frameworks and develop sequential control mechanisms analogous to human executive functions.

*Note: Figure translations are in progress. See original paper for figures.*

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