The Serial Position Effect in Divergent Thinking: A New Perspective on the Dynamic Generation Mechanism of Creative Ideas

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Abstract

The serial position effect in divergent thinking refers to the phenomenon where the number of ideas generated per unit time gradually decreases over time, while the originality of ideas progressively increases. Associative theory and the executive control hypothesis respectively focus on explaining individual differences and cognitive processing mechanisms underlying the serial position effect. Neuroimaging research indicates that throughout the idea generation phase, the serial position effect depends on sustained enhanced activation and cooperative interaction between the posterior default mode network and the salience network; during later stages of idea generation, temporoparietal alpha power and the cooperative pattern between the executive control network and the default mode network are enhanced. Future research should integrate techniques such as semantic and neural dynamic analysis to conduct in-depth investigations into the specific mechanisms, dynamic processing mechanisms, and influencing factors of the serial position effect, thereby providing novel perspectives for deconstructing the dynamic process of creative thinking.

Full Text

The Serial Order Effect in Divergent Thinking: A New Perspective on the Dynamic Mechanism of Creative Idea Generation

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Abstract: The serial order effect in divergent thinking (DT) is one of the most robust findings in creativity research, referring to the phenomenon where the number of generated ideas decreases while the originality of ideas increases over time during DT tasks. Association theory and executive control hypothesis offer complementary explanations, focusing on individual differences and cognitive processing mechanisms, respectively. Neuroimaging studies reveal that the serial order effect relies on sustained and enhanced activation and cooperation between the posterior default mode network and salience network throughout idea generation. In later stages of DT, alpha power in temporal-parietal regions increases, along with enhanced coordination between the executive control network and default mode network. Future research should integrate semantic and neural dynamic analyses to investigate the specific mechanisms, dynamic processing, and influencing factors of the serial order effect, thereby providing new perspectives for deconstructing the dynamic process of creative thinking.

Keywords: divergent thinking, serial order effect, creative idea, dynamic processes, neural mechanism

The serial order effect in divergent thinking (DT) tasks refers to the phenomenon where the number of ideas generated per unit time gradually decreases while the originality of ideas gradually increases over the course of a task (Christensen et al., 1957; Heinonen et al., 2016). This effect has been consistently observed across various DT tasks and age groups, representing one of the most classic findings in creativity research. Although numerous studies have investigated the neural mechanisms of creativity, the cognitive processes and corresponding brain activity patterns involved in different stages of creative thinking remain insufficiently understood (赵庆柏 et al., 2015). The serial order effect captures the dynamic nature of creative idea generation, and exploring its underlying cognitive and neural mechanisms can provide insights into the complex processes of creative thinking. This paper reviews over 60 years of research on the serial order effect in DT, examining its measurement methods, origins, and development. We synthesize theoretical foundations, behavioral findings, and brain mechanism studies, and propose future research directions from perspectives of cognitive models, dynamic processing mechanisms, and influencing factors, aiming to provide new breakthroughs for analyzing the dynamic mechanisms of creative idea generation.

1. Origins and Development of the Serial Order Effect

The discovery of the serial order effect in divergent thinking originated from Christensen et al. (1957), who were inspired by verbal fluency tasks showing higher idea generation rates in early phases that gradually decreased in later phases. Christensen and colleagues examined the relationship between idea generation rate and originality over time across multiple DT tasks, including plot titling, unusual uses tasks, and impossible scenarios. Participants were instructed to generate as many original ideas as possible within a specified time and to mark their ideas every two minutes. The study found that idea generation rate remained relatively stable throughout DT tasks, while originality increased over time.

Subsequent research has replicated and extended these findings. Ward (1969) conducted similar experiments with 7-8-year-old children, obtaining results largely consistent with Christensen et al. (1957). Although children with high fluency scores generated ideas faster than those with low fluency scores, they did not differ significantly in originality scores, timing of ceasing conventional ideas, or onset of generating unusual ideas. Unlike Christensen and Ward' s equal-time segmentation approach, Parnes and Meadow (1959) divided the total number of generated ideas into two equal halves to assess production patterns. They found that both trained and untrained college students reported more "good" ideas in the later half of idea generation. Phillips and Torrance (1977) administered verbal and figural DT tasks to 4th-6th graders, finding higher originality scores in later phases across all grades, though this effect was present only in verbal DT tasks. Milgram and Rabkin (1980) compared high- and low-originality individuals across 4th, 7th, and 12th grades, revealing more pronounced serial order effects in high-originality and older students, with more unusual ideas generated in later phases across all groups. Runco (1986) investigated patterns of flexibility and originality during idea generation, finding that both scores increased significantly in later phases, demonstrating the serial order effect. Recent studies using precise time-stamping of each idea have replicated the effect, showing decreasing idea quantity and increasing originality over time (Acar et al., 2019; Beaty & Silvia, 2012; Heinonen et al., 2016). Additionally, computational linguistic methods assessing semantic distance between sequential ideas have found that inter-idea semantic distance also increases over time, consistent with the pattern of increasing originality (Beaty & Dan, 2020). In summary, substantial evidence confirms the robust existence of the serial order effect across different age groups (children, adolescents, college students), various DT tasks (unusual uses, plot titling, impossible scenarios), and scoring methods (originality, flexibility, automated scoring).

2. Cognitive Mechanisms of the Serial Order Effect

While the serial order effect is well-established, a critical question concerns why ideas become more original over time in DT tasks. Early perspectives viewed creative idea generation as an automatic, low-effort, bottom-up cognitive process, with explanations grounded in associative theory and semantic activation spreading models (Mednick, 1962; Collins & Loftus, 1975). In this view, early-stage idea generation stems from low-level associative processes that facilitate spreading activation between concepts in one' s semantic network. This activation spreads from near to far, gradually accessing distant concepts at the network' s periphery over time. Consequently, individuals require more time when shifting from proximal, obvious concepts to remote, uncommon ones, but the resulting ideas become more original. More recently, executive control perspectives have emphasized top-down processing, arguing that increasing originality over time involves strategic use, interference inhibition, and goal-directed retrieval as key factors influencing creative idea generation (Beaty & Silvia, 2012).

2.1 Association Theory Explanations

According to association theory, creative idea generation involves spontaneously linking memory elements in new ways that meet specific requirements (Mednick, 1962). Early perspectives emphasized automatic processes, such as loose associations and disinhibition, that facilitate remote associations and intuitive thinking to stimulate creative ideas (Martindale & Hasenfus, 1978). This view builds on Collins and Loftus' s (1975) spreading activation theory of semantic processing, where concepts are represented as nodes in a semantic network connected by associative links. Association theory posits that creative idea generation is an automatic retrieval process that follows a gradual search pattern from proximal to distal activation in semantic space. Activation spreads from close, obvious associations to remote, unusual ones over time, with idea quality shifting from conventional to novel.

Within this framework, individual differences in creative ability can be explained by associative hierarchies or semantic network organization. Compared to low-creative individuals, high-creative individuals tend to have "flat" rather than "steep" associative hierarchies, with more flexible internal semantic structures that facilitate rich and diverse idea generation. Mednick (1962) proposed a negative correlation between association speed and total associations, suggesting that highly creative individuals show relatively slower but more stable associative responses in early task phases, enabling sustained production, whereas less creative individuals respond faster initially but quickly decline, producing fewer responses overall. Thus, individuals generating more responses in word association tests likely have flatter associative hierarchies, while those producing fewer responses have steeper hierarchies. When associative strength concentrates on a few stereotypical responses, the likelihood of creative solutions decreases. Earlier research also found a positive correlation between quantity and quality of ideas in DT tasks, where abundant idea production led to more creative outcomes (Parnes & Meadow, 1959). Recent studies using graph-theoretic analyses have found that high-creative individuals possess more flexible semantic network structures that facilitate activation spread (Christensen et al., 2018; Kenett et al., 2014). Flexible semantic networks enable high-creative individuals to show fewer stereotypical and common responses, more easily activate distal ideas, flexibly switch semantic categories, and discover similarities between concepts to form novel combinations (Hass, 2017; Heinen & Johnson, 2018; Kenett & Faust, 2019).

Regarding the serial order effect, association theory can independently explain both the rate and originality of idea generation. For associative fluency, research shows that high-creative individuals outperform low-creative individuals in continuous word association tasks, reflected in faster average association speeds (Mednick et al., 1964) and greater numbers of free associations (Benedek & Neubauer, 2013; Desiderato & Sigal, 1970; Piers & Kirchner, 1971) and chained associations (Levin, 1978). For associative uniqueness, high-creative individuals generate more novel than stereotypical associations (Benedek & Neubauer, 2013; Riegel et al., 1966), though both high- and low-creative individuals produce more unique associations in later task phases (Olczak & Kaplan, 1969; Piers & Kirchner, 1971). However, as association theory emphasizes, high-creative individuals outperform low-creative individuals in both quantity and quality across early and late phases. Thus, association theory better explains individual differences in creative ability rather than underlying cognitive process differences. Combined with semantic activation spreading models, creative idea generation depends on conceptual activation and transmission over time. Activation spreads from one concept to another, with proximal strong associations activating before distal weak associations, leading to novel ideas. Given sufficient time, activation gradually reaches peripheral concepts, producing original ideas. This perspective has been repeatedly confirmed in serial order effect research, where later-phase ideas show significantly higher originality than early-phase ideas, albeit with increased time costs (Agnoli et al., 2020; Christensen et al., 1957).

2.2 Executive Control Explanations

Recent research has increasingly focused on executive control components in creativity, arguing that top-down control processes play crucial roles in creative idea generation. This perspective offers new explanations for the serial order effect. Beaty and Silvia (2012) proposed that creative idea generation involves multiple executive control processes, including strategy selection and use, cognitive inhibition, and switching (e.g., shifting to remote, unusual ideas when fixated). Beaty et al. (2014) further found that creative idea generation depends not only on free association but also on goal-directed, controlled retrieval processes, where free association enables rapid conceptual activation in semantic networks while controlled processing ensures goal-oriented semantic retrieval. These findings refine the dual-process theory of creativity (Finke et al., 1992), suggesting that both generation and evaluation phases require top-down and bottom-up processing (Kleinmintz et al., 2019). Thus, multiple executive control components may participate throughout creative idea generation, playing different roles at different stages (Bai et al., 2021; Miroshnik & Shcherbakova, 2019).

First, strategy selection and use during idea generation produce the serial order effect. Gilhooly et al. (2007) revealed how individuals select and change cognitive strategies over time when completing the Alternative Uses Task (AUT). In Experiment 1, participants verbalized their thought processes while generating unusual uses for objects. Analysis of these verbal protocols identified four strategies: memory retrieval, property use, broad use, and disassembly. Participants typically prioritized memory retrieval, directly extracting stored "old" ideas from memory. When retrievable ideas were exhausted, they shifted to other strategies to generate "new" ideas. In this process, episodic memory strategies dominated early phases, followed by more abstract semantic retrieval strategies based on object properties. Memory retrieval strategies correlated with fluency, while memory retrieval and disassembly strategies related to novelty. In Experiment 2, the relationship between strategy use and executive control was examined. After completing the AUT, participants reported which ideas were "new" and then performed category and letter fluency tasks. Results showed "new" ideas emerged later but were more novel than "old" ideas. Category fluency performance positively predicted "old" idea production, while letter fluency positively predicted "new" idea production. The authors concluded that "old" ideas stemmed from early-phase memory retrieval, while "new" ideas arose from late-phase property use or disassembly strategies. Furthermore, individuals with stronger executive control abilities preferred non-memory retrieval strategies in the AUT. Subsequent studies using old/new scoring methods have consistently found that "new" ideas are more original than "old" ideas and typically appear after them (Benedek et al., 2014; Benedek et al., 2018; Ding et al., 2021; Miroshnik & Shcherbakova, 2019; Silvia et al., 2017). This specific idea generation process in DT tasks reveals the temporal structure of strategy use underlying the serial order effect: as time progresses and individuals exhaust "old" ideas via memory retrieval and shift to other strategies for "new" ideas, originality increases. While strategy selection explains the increase in novelty over time, it does not fully account for the increased time costs in later idea generation.

Second, category switching during idea generation contributes to the serial order effect. Acar and Runco (2017) examined relationships between category switching, category staying, and idea generation time in verbal and figural DT tasks. Participants verbally reported ideas as they occurred to record individual idea generation times. Results showed that category switching required approximately five seconds more than generating new ideas within the same category. In other words, entering different conceptual categories to generate new ideas required more time. This difference was more pronounced in figural than verbal creative tasks, with category switching requiring an additional 2.5 seconds in figural tasks. In subsequent research, Acar et al. (2019) found that category switching time was not constant throughout the idea generation process. Individuals spent the most time on category switching in later phases, significantly more than in early phases. This increased time cost positively correlated with idea originality. The authors argued that forming new ideas through category switching to connect distant concepts required more time than simply extracting known ideas from experience. Individual differences research shows that individuals with high intelligence and working memory capacity more easily achieve category switching, while those with lower intelligence and capacity show lower switching frequencies, generating fewer ideas and fewer creative ideas in the AUT (Unsworth et al., 2011). Additionally, high-switching ability individuals generate increasingly original ideas over time, whereas low-switching ability individuals show no such temporal increase in originality (Wang et al., 2017). Researchers suggest that individuals with lower intelligence and switching ability have greater difficulty controlling attention and cognitive resources effectively, resulting in lower category switching frequencies during idea generation (Unsworth et al., 2011; Wang et al., 2017). Category switching research explains why time costs increase sequentially: retrieval within established categories is efficient, but as time progresses, individuals must exit established categories and search in new ones, increasing time costs, especially since later ideas depend more heavily on category switching. Similar patterns appear in verbal fluency tasks, where individuals first exhaust obvious categories before switching to new ones when reaching impasses (Unsworth et al., 2011), increasing time costs without necessarily increasing novelty.

Third, executive functions relate to the serial order effect in DT. Beaty et al. (2012) proposed that top-down control processes, rather than just activation spreading models, explain the serial order effect. Creative idea generation requires inhibitory control to exclude close, obvious, or task-irrelevant ideas, and working memory to maintain task-relevant goals, both dependent on executive functions (Storm & Angello, 2010; Storm & Patel, 2014). Camarda et al. (2018) used a dual-task paradigm to manipulate cognitive load during idea generation, investigating inhibitory control' s role. Participants performed a Stroop task concurrently with a DT task (generating creative solutions to prevent eggs from breaking when dropped from 10 meters). Results showed that inhibitory control load reduced both fluency and flexibility of creative ideas. A recent study using a similar dual-task paradigm (concurrent working memory and AUT tasks) found that originality increased over time, showing the serial order effect. Interestingly, high and low load conditions produced similar quality ideas in early phases, but high load reduced quality slightly in later phases, suggesting that executive control processes are more involved in later-stage creative idea generation (Kleinkorres et al., 2021). Consistent with Camarda et al., flexibility decreased over time, suggesting that flexible thinking becomes less applicable for sustained original idea generation. Thus, the shift from flexible to persistent thinking may explain why executive functions increasingly influence creative idea generation. Additionally, Beaty et al. (2019) examined dynamic retrieval and control processes in creative idea generation (Chrysikou, 2019; Volle, 2018). Using AUT cues with low versus high association strength ("low-fan" vs. "high-fan"), they found that participants generated more original but fewer ideas with low-fan cues, and more numerous but less original ideas with high-fan cues. Both cue types showed serial order effects, but originality for low-fan cues increased more over time than for high-fan cues. Furthermore, individuals with higher executive control ability showed greater originality increases for low-fan versus high-fan cues. This suggests that over-activation of semantically shared concepts in long-term memory interferes with creative idea generation, while executive control helps overcome interference from close semantic connections, explaining why high-fan cues also show serial order effects. For low-fan cues, executive control drives top-down search processes, promoting strategy switching and forced connections to compensate for sparse semantic connections, thereby generating novel ideas (Volle, 2018). Executive functions encompass cognitive abilities closely related to interference inhibition, strategy selection, and cognitive switching, providing a comprehensive explanation for the serial order effect without fundamentally negating association theory. However, most research has examined executive functions from an individual differences perspective, with less investigation of which executive functions operate when during idea generation—a critical issue for future research.

3. Neural Mechanisms of the Serial Order Effect

While behavioral research has extensively examined the serial order effect and its mechanisms, neural mechanism studies remain relatively scarce. Electroencephalography (EEG) offers high temporal resolution suitable for investigating cognitive and neural oscillatory mechanisms associated with temporal dynamics in creative idea generation (叶超群 et al., 2021). Fink and Benedek (2014) systematically reviewed EEG studies on creative thinking (especially DT) and alpha band (8-12 Hz), finding that the most robust neural pattern during creative idea generation is increased alpha oscillations in prefrontal and posterior parietal regions, reflecting increased internally-directed attention and interference inhibition demands. Specifically, alpha power sensitivity to creative cognition manifests as: (1) higher alpha power with greater task creativity demands; (2) higher alpha power with more novel ideas; and (3) higher alpha power in more creative individuals. Based on these findings, Fink and Benedek proposed analyzing alpha power changes to investigate creative thinking processes.

Schwab et al. (2014) first examined temporal dynamics of alpha band activity during individual creative idea generation in the AUT. Dividing the 10-second pre-idea generation EEG into three equal segments, they found U-shaped alpha power changes over time in right hemisphere temporal and parietal regions. Alpha power increased substantially during initial idea generation, decreased in the middle period, and increased again in the final phase. The authors interpreted this unique pattern as reflecting distinct cognitive processes across idea generation phases. Initial alpha enhancement relates to inhibitory control and memory retrieval, as individuals tend to recall conventional ideas directly from memory. Subsequent alpha reduction may indicate decreasing memory retrieval, paving the way for more creative and imaginative thinking (Gilhooly et al., 2007). Final-phase alpha enhancement likely marks internally-directed attention to facilitate specific memory searches and more complex creative thinking. Two recent figural DT studies reported similar results. Jaarsveld et al. (2015) found significantly increased task-related upper alpha band (10-12 Hz) power during initial and final phases of a figural creation test. Rominger et al. (2019) found increased upper alpha power changes during idea elaboration (late phase) compared to generation (early phase). Further analysis revealed different alpha activity patterns across creative ability levels, with participants generating more original ideas showing higher alpha power at creative process onset and conclusion. This U-shaped alpha pattern accompanied increased functional connectivity between early frontal-parietal-occipital regions, indicating activation of top-down executive control processes. Initial alpha increases may reflect more associative thinking and memory processes, while later increases may reflect executive control related to idea elaboration and evaluation. These findings demonstrate dynamic brain activity changes reflecting cognitive demands in DT, consistently showing that creative idea generation follows a temporal pattern of task-related alpha power changes, likely reflecting a shift from initially relying on internally-directed attention to generate possible ideas to subsequently relying more on executive control to select optimal ideas, requiring a transition from bottom-up to top-down processing to facilitate creative idea generation.

Furthermore, three recent studies examined temporal dynamics of alpha activity during multiple consecutive idea generation in the AUT, revealing deeper insights into neural patterns underlying the serial order effect. Wang et al. (2017) investigated relationships between executive functions (inhibition, switching, updating) and the serial order effect, finding that individuals with lower inhibitory control showed stronger left versus right prefrontal alpha activity in early idea generation phases, while high inhibitory control individuals showed no such phase differences. The authors suggested that high inhibitory control individuals use fewer cognitive resources to inhibit dominant ordinary ideas in early phases, whereas low inhibitory control individuals require more top-down control. However, Kraus et al. (2019) found that alpha power increased overall with consecutive idea generation, with left hemisphere alpha power increasing faster than right hemisphere alpha during the AUT, while the opposite pattern appeared in category fluency tasks. This suggests that alpha power changes are specific to creative task demands. Similarly, Agnoli et al. (2020) examined dynamic brain activity patterns when individuals generated four consecutive ideas in the AUT, finding overall alpha power increases over time, particularly in right central, temporal, and parietal regions, with alpha changes correlating with increasing idea novelty. These results suggest that early idea generation involves more long-term memory retrieval, while later idea generation involves more top-down executive control. Overall, increasing alpha power with consecutive idea generation reflects growing reliance on top-down executive control processes to actively inhibit dominant close associations, facilitate flexible conceptual category switching, and reorganize remote associative information, making generated ideas increasingly innovative over time.

Beaty et al. (2015) used fMRI to examine dynamic whole-brain functional connectivity changes during idea generation in the AUT. Compared to a control condition (thinking about object features), the novelty condition (thinking of novel uses) activated extensive brain regions, including the default mode network (DMN), executive control network (ECN), and salience network (SN). The DMN is typically associated with internally-directed and spontaneous associative processes such as mind-wandering, future imagination, and mental simulation (Beaty et al., 2016; Wise & Braga, 2014). The ECN participates in externally-directed attention processes such as working memory, conceptual integration, and inhibitory control (Beaty et al., 2016; Beaty et al., 2019; Chrysikou, 2019). The SN coordinates dynamic switching between DMN and ECN, facilitating attentional resource reallocation, such as shifting internal to external attention during creative idea generation to orient away from dominant and habitual ideas (Beaty et al., 2016). The authors then segmented the 12-second idea generation period into 2-second intervals to examine dynamic brain network changes, finding enhanced coupling between DMN and SN in early AUT phases, and enhanced DMN-ECN coupling in later phases. These dynamic functional network couplings suggest that creative idea generation involves cooperation among brain networks related to spontaneous association, cognitive control, and semantic memory retrieval to focus internal attention and execute top-down cognitive control. Heinonen et al. (2016) designed a novel probe to investigate neural mechanisms of the serial order effect in DT. Participants pressed a button when they generated new ideas during the AUT without verbal reporting (reporting occurred after scanning). Behavioral results showed the classic serial order effect pattern, while neuroimaging data revealed that bilateral insula and dorsal anterior cingulate cortex (key SN regions) dominated new idea generation, with activation increasing across serial positions. Additionally, DMN regions including bilateral precuneus/cuneus, posterior cingulate cortex, and right inferior parietal lobule became increasingly active with serial position.

Despite different analytical approaches, these studies converge at the brain network level: the DMN participates throughout creative idea generation, while the SN may coordinate dynamic switching between DMN and ECN. Regarding ECN involvement, although both studies agree on its role, Heinonen et al. did not find classic ECN regions such as dorsolateral prefrontal cortex or medial prefrontal cortex. Instead, they defined anterior cingulate cortex as a key ECN region, though this area is typically classified as DMN or SN. This discrepancy may stem from different reporting methods: Beaty et al. used single-response think-aloud reports involving idea reprocessing (selection, evaluation, refinement, and response), thus engaging ECN more heavily; Heinonen et al. used a no-report design facilitating internal thought fluency, thus engaging DMN more and ECN less. This suggests that ECN’ s role in creative idea generation depends on task context and changes accordingly. Combined with EEG findings of U-shaped alpha power changes, we propose that in early idea generation, the ECN centered on lateral prefrontal cortex acts on lateral temporal regions related to semantic memory to inhibit dominant and conventional ideas. During this phase, DMN and ECN do not co-activate but show a sequential reciprocal pattern. Over time, as interference from dominant ideas decreases and semantic search space and distance from stimulus concepts increase, the lateral prefrontal cortex-dominated ECN shifts to controlled semantic retrieval, including representational transformation, remote conceptual integration, and selection/evaluation of potential ideas in working memory. This is reflected neurally by ECN-DMN coupling, particularly co-activation of lateral prefrontal cortex with inferior frontal gyrus, dorsomedial prefrontal cortex, and hippocampus (part of DMN). In summary, neuroimaging research indicates that creative idea generation relies on dynamic coupling among DMN, ECN, and SN, though the precise mechanisms producing the serial order effect require further investigation.

4. Summary and Outlook

This review synthesizes theoretical and empirical research on the serial order effect, demonstrating that sequential idea generation depends on multiple cognitive capacities involving both associative and executive processes, as well as coordinated activity in associated brain regions and networks. However, neural mechanism research on the serial order effect remains limited, with explanatory frameworks largely derived from existing cognitive and neural models of creative thinking. Future research should incorporate dynamic characteristic models of the serial order effect, including quantification of sequential idea dynamics, processing stages, stage interactions, and underlying brain mechanisms, to explore dynamic mechanisms of creative idea generation through in-depth analysis of the serial order effect. Given the importance of the serial order effect for understanding creative idea generation, future research should address the following aspects:

4.1 Investigating Specific Mechanisms of the Serial Order Effect in Divergent Thinking

Early research identified serial order effects in perception (Sperling, 1960), memory (Conrad, 1964), and free association tasks. Memory studies often use serial recall, cued recall, and free recall paradigms to explore temporal serial position phenomena and mechanisms (Lewandowsky & Farrell, 2008). Similar to DT, verbal fluency tasks also exhibit serial order effects and involve multiple executive control processes, particularly cue generation, category switching, and interference management (Unsworth et al., 2011). Logan (2018) developed a Context Retrieval and Updating (CRU) model to explain experts' automated responses, such as sequential output behavior in automated typing. Unlike successive inhibition models (Rumelhart & Norman, 1982) and sequential competition models (Grossberg, 1978), the CRU model emphasizes that contextual information changes from individual responses alter activation strength of subsequent potential responses (including actions, recall, associations), making iterative contextual changes key to sequential responses. Through simulation and empirical data, Logan (2018) found that different forms of serial order effects may be explained by the same underlying mechanism, suggesting that the CRU model generalizes to perception, memory, and action. The CRU model posits that concepts in problem contexts activate in parallel but compete, with activation strength proportional to similarity to current context. As responses occur, context updates and concept activation strength changes gradiently, leading to automated selection and response, producing serial order effects. Although DT serial order effect research is emerging, mechanistic explanations remain based on theoretical models from creativity research (Beaty et al., 2014; Mednick, 1962). As a serial order effect phenomenon, whether DT' s serial order effect can be explained by the CRU model awaits empirical investigation. Both association theory and executive control hypotheses emphasize concept activation and inhibition in static semantic networks, whereas CRU de-emphasizes inhibition, focusing more on dynamic relationships among contextual iteration, concept activation, and response selection. In DT tasks, sequential responses may dynamically adjust individuals' semantic networks. The CRU model could derive relationships among sequential responses based on semantic network dynamics, rather than merely explaining them through activation connections and mutual inhibition. We propose that CRU' s generalizability can explain partial effects of the DT serial order phenomenon, while aspects not explained by CRU may reflect specific cognitive processing mechanisms. Future research should combine CRU modeling and computational approaches to investigate serial order effect mechanisms.

4.2 Characterizing Dynamic Features of the Serial Order Effect in Divergent Thinking

Numerous studies have used neuroimaging to analyze dynamic mechanisms of creative thinking. For example, Beaty et al. (2016) investigated brain network coordination during DT using task-based functional connectivity analysis, finding DMN dominance in early idea generation phases and DMN-ECN co-dominance in later phases. Neuroimaging studies of musical improvisation have found similar brain network patterns (Belden et al., 2019; Mota et al., 2020). However, these studies often adopt a brain-centered, data-driven approach, inferring potential cognitive mechanisms from brain activation patterns. Since interpretations of brain networks or regions responsible for creativity are non-specific, these studies have not effectively addressed dynamic mechanisms of creative thinking processing. The continuous generation of ideas over time in DT characterizes the dynamic thinking process from problem initial state to solution state (Jaarsveld et al., 2015). Although these discrete sequential ideas do not reflect the complete creative thinking process, they partially capture the continuous dynamics of creative idea generation. Existing research tends to treat sequential ideas as stage-based processing, comparing novelty and brain activity patterns across different positions or time periods to explain underlying mechanisms (Wang et al., 2017). However, Volle (2017) proposed, based on association theory, that creative idea generation is an interdependent process where ideas are continuous and dependent on one another. We suggest that quantifying relationships among sequentially positioned creative ideas can partially depict this continuous process. For example, latent semantic analysis (LSA) can compute similarity or semantic distance between cue objects and ideas, as well as between consecutive ideas (Gray et al., 2019), thereby characterizing trends and functional relationships among idea sequences generated from cue objects. Additionally, Yoed et al.' s construction and analysis of creative semantic networks demonstrated that semantic distance between ideas can measure novelty, and graph-theoretic methods can map sequential ideas onto semantic structure space, enabling network analysis metrics such as modularity and node centrality to measure relationships among creative ideas, providing methodological guidance for investigating dynamic mechanisms of the serial order effect (Kenett & Faust, 2019).

4.3 Revealing Dynamic Neural Mechanisms of Sequential Idea Generation in Divergent Thinking

Current neural mechanism studies of the DT serial order effect have examined brain activity pattern differences across temporal stages. From a continuity perspective, these studies have only explored differences between early and late idea generation phases. Based on this review' s core argument, we propose that the serial order effect offers a new window for investigating dynamic mechanisms of creative thinking. Building on existing research, future studies examining how the brain drives dynamic creative idea generation will yield greater theoretical value. This problem can be investigated at two levels: First, using neural activity pattern similarity to examine whether sequential ideas are interdependent—for example, whether neural activity pattern similarity differs between category switching versus within-category phases. Alternatively, representational similarity analysis can investigate dynamic coupling pattern changes among sequential ideas to parse neural bases of interdependent versus independent idea generation. Second, using sliding window dynamic network analysis (Sun et al., 2019; Rabinovich et al., 2020) and hidden Markov models (Anderson et al., 2016) to deconstruct brain state quantity, switching frequency, and transition pathways throughout the entire DT process, then identifying time windows for creative ideas and parsing their specific brain activity patterns. Additionally, relationships between brain activity states and idea originality during idea generation can be examined. Furthermore, dynamic causal modeling (Friston et al., 2003; Tik et al., 2019; Vartanian et al., 2018) and Granger causality analysis (Seth et al., 2015; Duan et al., 2020) can investigate connectivity patterns and information flow direction in key brain regions (e.g., dorsolateral prefrontal cortex) during each idea generation, clarifying brain-driven patterns of dynamic idea generation.

4.4 Exploring Influencing Factors of the Serial Order Effect in Divergent Thinking

Both DT and other creative problem-solving tasks require organizing and processing information within time constraints to generate appropriate and novel solutions. An implicit premise of the serial order effect is that individuals need substantial time to most likely produce unique answers. But how much time optimally facilitates novel idea generation? A meta-analysis found that free-time conditions produced higher average efficiency (i.e., quality per idea) in DT than time-limited conditions. However, longer is not always better, as idea quality shows an inverted J-pattern over extended time, with originality declining in later phases (Paek et al., 2021). Research also shows that originality change functions depend not only on time but also on multiple factors such as executive functions, metacognition, motivation, and time pressure perception (Beaty & Silvia, 2012; Jia et al., 2019; Paek et al., 2021). For example, 家晓余 (2018) found that individuals holding a malleable view of creativity (an internal motivation) could achieve more original ideas through cognitive persistence.

Additionally, investigating influencing factors of the serial order effect offers insights for creativity education, such as training executive functions, enhancing internal motivation, and optimizing response time to help students access creative ideas and unlock creative potential. Therefore, future research should examine internal and external factors influencing the serial order effect to clarify its boundary conditions.

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Serial order effect during divergent thinking: a new perspective on the dynamic mechanism of creative thought processes

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Abstract: The serial order effect in divergent thinking (DT) is one of the most robust findings in creativity research. This effect refers to the phenomenon that the number of generated ideas decreases, whereas the originality of ideas increases across time while performing DT. Both association theory and executive control hypothesis contribute to explaining the serial order effect, but the association theory and the executive control hypothesis focus on explaining individual differences in the serial order effect and cognitive processing, respectively. Previous neuroimaging studies have found gradually increased activation in the posterior areas of the posterior default network (i.e., precuneus and posterior cingulate gyrus) and the salience network (i.e., bilateral insula and dorsal anterior cingulate gyrus) was associated with the generation of serial novel ideas. In the later stage of DT, the energy of alpha of the temporal-parietal region, as well as the cooperation between the executive control network and the default network is increased, suggesting that internally-directed cognitive processes play a key role for the originality of the later serial ideas. Future research needs to combine cognitive and computational models, semantic analysis, brain dynamic analytical approaches, and representational similarity analysis to explore the cognitive and neural mechanisms of the serial order effect, as to provide a new perspective for deconstructing the dynamic process of creative thinking.

Key words: divergent thinking, serial order effect, creative idea, dynamic processes, neural mechanism