Sequential Dependency Effect: A Novel "Historical Effect"

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Abstract

Since 2014, researchers have discovered a novel historical effect in visual processing—serial dependence effect (an attractive processing bias whereby processing of the current stimulus shifts toward the direction of previous stimuli). Recent studies have revealed that this effect is ubiquitous across various levels of visual processing, encompassing both low-level features (e.g., orientation, spatial location, numerosity) and high-level attributes (e.g., identity, attractiveness, aesthetic value). Its origins are remarkably complex, involving sensory encoding, feedback modulation from higher cortical areas, working memory, decision templates, cascades of perception and decision-making, among others, thereby reflecting the projection of past processing traces at different hierarchical levels onto current cognition. A substantial body of research has emerged investigating the typical characteristics, influencing factors, and cognitive and neural mechanisms of this effect; however, serious controversies persist, necessitating urgent and thorough investigation and clarification by researchers.

Full Text

Preamble

Serial Dependence Effect —A Novel "History Effect"

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Abstract

Since 2014, researchers have identified a novel history effect in visual processing—the serial dependence effect, an attractive processing bias whereby current stimulus processing is pulled toward the orientation of preceding stimuli. Recent studies have revealed that this effect pervades multiple levels of visual processing, encompassing both low-level features (orientation, spatial location, numerosity) and high-level attributes (identity, attractiveness, aesthetic value). Its origins are remarkably complex, including sensory encoding, feedback modulation from higher cortical areas, working memory, decision templates, and cascades of perception and decision-making, reflecting projections of past processing traces onto current cognition from different hierarchical levels. While numerous studies have emerged investigating the typical characteristics, influencing factors, and cognitive/neural mechanisms of this effect, significant controversies persist, urgently requiring deeper exploration and clarification.

Keywords: serial dependence effect, cognitive and neural mechanisms, perception, memory, decision-making

Numerous studies have demonstrated that past stimuli influence the processing of current stimuli (de Lange et al., 2018; Joos et al., 2020), a phenomenon broadly termed "history effects" (Liberman et al., 2014). Previously discovered history effects—including priming effects (Maljkovic & Nakayama, 1994), adaptation effects (Webster, 2012), and sequential effects (Lockhead, 2004)—contribute to maintaining visual perceptual stability and sensitivity. Since 2014, researchers have identified a new history effect in visual perception: the serial dependence effect. Over the past eight years, related research has exploded. This article reviews recent advances in understanding the typical characteristics, influencing factors, and cognitive/neural mechanisms of this effect, with particular emphasis on 梳理 the major theoretical explanations for its origins, and concludes by proposing several research questions and future directions for the field.

Serial dependence effect manifests as systematic and stable biases in our responses to current stimuli toward preceding stimuli (Fischer & Whitney, 2014). The pioneering work of Fischer and Whitney (2014) provided the first systematic, comprehensive, and complete experimental evidence for this effect. In their study, participants viewed a randomly oriented grating on each trial and were asked to adjust a test stimulus to match its orientation. The error distribution in matching reports revealed that participants' reports were systematically biased toward the grating orientation from the previous trial. For instance, when the previous trial' s grating orientation was more clockwise than the current one, participants' judgments of the current grating orientation were shifted further clockwise than its actual orientation—an attractive influence. Since 2014, research on serial dependence has grown exponentially. Researchers have discovered that this effect exists across various levels of visual processing: low-level features including orientation (Fischer & Whitney, 2014), spatial location (Manassi et al., 2018), numerosity (Corbett et al., 2011; Fornaciai & Park, 2018b), time perception (Roseboom, 2019), motion (Alais et al., 2017), visual variance (Suarez-Pinilla et al., 2018), and ensemble coding (Manassi et al., 2017), as well as high-level attributes including face identity (Liberman et al., 2014), facial attractiveness (Ho & Newell, 2020; Pegors et al., 2015; Xia et al., 2016), aesthetic value (Kim et al., 2019), and emotion (Liberman et al., 2018). This suggests that serial dependence may reflect a visual processing mechanism involved in all aspects of visual processing. Therefore, researchers have speculated (Fornaciai & Park, 2020b) that serial dependence may reduce noise by exploiting short-term correlations in cognitive processing, serving as an adaptive mechanism that promotes perceptual stability and continuity while conserving neural resources for visual processing.

2. Typical Characteristics of Serial Dependence: Distinctions from Other History Effects

Serial dependence exhibits distinct characteristics that differentiate it from other well-known history effects. Priming, adaptation, and sequential effects all demonstrate how prior experience influences current perception and responses, but experimental evidence reveals that serial dependence is a novel phenomenon.

First, adaptation studies show that preceding adaptation stimuli cause subsequent stimulus processing to perceive the adapted feature direction as repelled away (Anstis et al., 1998), whereas serial dependence makes current stimuli more similar to previous ones. Second, adaptation' s negative aftereffects have specific conditions and characteristics (Thompson & Burr, 2009)—typically requiring highly salient stimuli with relatively long exposure, showing spatial specificity, retinotopic dependence, and being largely unaffected by attention. In contrast, serial dependence is strongest with weak stimuli, exhibits temporal and spatial tuning characteristics, and is highly attention-dependent (Cicchini et al., 2017; Fischer & Whitney, 2014; Fritsche & de Lange, 2019). Third, priming effects typically manifest in reaction times (Maljkovic & Nakayama, 1994) and improve stimulus discriminability (Sigurdardottir et al., 2008). Serial dependence, however, does not affect reaction times or enhance perceptual discriminability (Liberman et al., 2014). Additionally, priming effects are attention-independent and can occur with subliminal stimuli outside awareness (Francken et al., 2011). Conversely, serial dependence only occurs with consciously perceived stimuli (Kim et al., 2020; Rafiei et al., 2021). Finally, adaptation and priming effects have been shown to generalize across different modalities and can occur cross-modally (Arrighi et al., 2014). However, current experimental evidence indicates that serial dependence primarily appears in the visual modality (whether stable cross-modal serial dependence occurs requires more evidence) and cannot occur cross-modally (Fornaciai & Park, 2019a).

These differences do not imply that priming, adaptation, and serial dependence are completely unrelated, but rather that they are clearly distinguishable phenomena. Their complementary roles in perceptual processing constitute a topic for future research (Liberman et al., 2016). Indeed, many studies have shown that attractive serial dependence and repulsive adaptation aftereffects can co-occur within a single task (Fischer & Whitney, 2014; Pascucci et al., 2019).

3. Factors Influencing Serial Dependence

Existing research has explored numerous factors influencing serial dependence, including attentional modulation, stimulus feature modulation, and sensory uncertainty modulation. However, results remain inconsistent, and the conditions for occurrence, influencing factors, and manifestations across different stimuli require further investigation.

3.1 Attentional Modulation of Serial Dependence

A crucial characteristic of serial dependence is its relationship with attention. Fischer and Whitney (2014) used Gabor stimuli arranged in a circular pattern at different spatial locations and found that spatial attention critically influences serial dependence—the orientation bias in the current trial followed the orientation of the attended stimulus from the previous trial, not the stimulus that spatially overlapped with the current trial but was unattended. In other words, a salient feature of serial dependence is the integration of information across spatial locations covered by attention at adjacent moments. Additionally, Fornaciai and Park (2018b) found that in a simultaneous comparison task (where the inducer stimulus causing serial dependence did not spatially overlap with fixation), no significant serial dependence occurred when attention was focused at fixation, but it emerged when attention was focused on the inducer stimulus location, indicating that serial dependence requires strong attention to the stimulus. Recently, Kim et al. (2020) used a binocular rivalry paradigm and found that only consciously perceived stimuli could produce attractive biases on subsequent stimuli. Rafiei et al. (2021) combined visual search tasks with stimulus reproduction tasks to investigate serial dependence and similarly found that only attended stimuli produced serial dependence, while ignored stimuli produced repulsive effects on subsequent stimuli. Furthermore, researchers have found that attention can modulate not only the magnitude of serial dependence (manifested as bias size) but also its width (manifested as the range of stimuli showing attractive bias) (Fritsche & de Lange, 2019). Attentional modulation of serial dependence suggests that, unlike visual adaptation, serial dependence is not limited to retinotopic spatial locations, implying that the effect does not operate solely at the perceptual level but may involve active high-level processing.

Since serial dependence occurs not only for specific stimulus features (e.g., orientation) but also for complex objects (e.g., faces), an interesting question concerns whether attentional modulation operates at the feature level or object level—that is, whether it involves attention to specific (task-relevant) features within a stimulus or attention to the stimulus as a whole (Liberman et al., 2014; Manassi et al., 2017). Some researchers previously hypothesized that serial dependence originates at the object level (Liberman et al., 2014). For example, in face recognition, serial dependence is unaffected by viewpoint changes—suggesting that face-based serial dependence occurs at an object-centered representational level rather than relying on low-level stimulus features (Liberman et al., 2014; Turbett et al., 2021). If so, as long as an object is spatially attended, attention to specific stimulus features may not be necessary. However, Suarez-Pinilla et al. (2018) found that when investigating serial dependence in visual variance, the effect only occurred when observers attended to and reported the visual variance of previous motion stimuli rather than their average orientation. Fritsche and de Lange (2019) further found that in orientation reproduction tasks, serial dependence was modulated by feature-based attention. These findings indicate that under certain experimental conditions, serial dependence can occur at the feature level, with the necessary condition being attention to task-relevant features (Fritsche & de Lange, 2019). Summarizing these studies, the mode of attentional modulation appears closely related to stimulus type: for low-level features such as orientation and ensemble visual variance, attentional modulation may occur at the feature level; for high-level complex objects such as faces, attentional modulation can also operate at the object level.

3.2 Stimulus Feature Modulation of Serial Dependence

Fischer and Whitney (2014) used orientation stimuli and found that serial dependence magnitude increased with larger orientation differences between consecutive trials, peaking at a difference of 27.78°, with the relationship between inter-trial difference and response bias (representing serial dependence magnitude) fitting the first derivative of a Gaussian function. However, when differences became larger, serial dependence decreased and gradually disappeared. Numerous subsequent studies (Cicchini et al., 2017; Huffman et al., 2018) have confirmed that serial dependence only occurs within a certain range of similar stimuli; when stimulus differences are large, repulsive negative aftereffects similar to adaptation emerge instead (Alais et al., 2017). Additionally, research has found that in the orientation dimension, serial dependence is not equivalent across directions: oblique orientations produce larger serial dependence effects than horizontal or vertical orientations (Cicchini et al., 2017), indicating that serial dependence is related to stimulus orientation characteristics.

Huffman et al. (2018) found that when color served as an irrelevant feature, it did not affect serial dependence for task-relevant features. This finding further supports the notion that serial dependence is not limited to the object level but can occur at specific feature levels, unaffected by task-irrelevant stimulus features. Fischer et al. (2020) more deeply explored stimulus feature influences on serial dependence, using the working memory framework theory (Oberauer & Lin, 2017) to categorize stimulus features into content features and context features. Their results showed that for objects, context features (color, serial position) only influenced serial dependence when relevant to the current task, whereas spatial location affected serial dependence regardless of task relevance, demonstrating the special status of spatial location.

Furthermore, recent studies have found that serial dependence can occur across stimulus formats (when the same feature dimension is presented differently across trials, e.g., simultaneous vs. sequential presentation for numerosity, Fornaciai & Park, 2019a) and across different response methods (when response methods differ across trials, e.g., alternating between two reproduction methods for orientation, Cicchini et al., 2017), but cannot occur across different stimulus feature dimensions (i.e., cannot directly generalize between different feature dimensions across trials, Togoli et al., 2021). Togoli et al. used stimuli containing both numerosity and temporal dimensions, with pre-cues indicating which dimension to attend to, allowing both dimensions to enter attentional encoding. Their results showed that serial dependence only occurred between identical stimulus dimensions. This indicates that, unlike adaptation effects that can generalize across stimulus feature dimensions (Kohn, 2007), serial dependence exhibits high stimulus feature selectivity. From the perspective of maintaining visual processing stability, this high feature selectivity is necessary, as it can smooth perceptual noise while preventing excessive integration across feature dimensions.

3.3 Modulation by Sensory Uncertainty

Serial dependence may also be modulated by sensory uncertainty (Samaha et al., 2019). Fornaciai and Park (2019a) found that serial dependence magnitude correlates with just-noticeable differences (JND, representing precision of perceptual estimates). That is, under conditions of higher uncertainty (indexed by lower precision), the visual system may rely more heavily on past input to reduce or improve current sensory uncertainty. Ceylan et al. (2021) also found that stimuli with lower spatial frequency (higher sensory uncertainty) produce larger serial dependence effects. Taubert et al. (2016) used face stimuli with different stability characteristics (stable gender features vs. unstable expression features) and found attractive serial dependence for gender features but repulsive effects for expression features. These results suggest that integration strategies (attractive vs. repulsive) depend on the inherent stability of stimulus features. Similarly, Kok et al. (2017) showed that serial dependence for facial attractiveness is influenced by face familiarity, with stronger effects for unfamiliar faces (higher perceptual uncertainty). This aligns with the rational observer model developed by Cicchini et al. (2018), which posits that serial dependence is directly constrained by stimulus uncertainty and similarity between current and previous stimuli.

4. Cognitive and Neural Mechanisms of Serial Dependence

Currently, the most controversial topic in this field concerns the cognitive and neural mechanisms underlying serial dependence, particularly its origin. Initially, researchers proposed that, like adaptation, serial dependence originates at the perceptual level (Fischer & Whitney, 2014). However, subsequent studies have provided evidence pointing to working memory (Bliss et al., 2017) or decision-making levels (Fritsche et al., 2017), supporting the view that serial dependence is a post-perceptual effect arising from interference in working memory content or residual traces of decision-making. This perceptual/post-perceptual dichotomy has been widely used to explain serial dependence mechanisms. Traces of serial dependence have been discovered across various cognitive processing stages from stimulus input through perception and memory to post-perceptual decision-making. Based on this, researchers have proposed explanatory models grounded in different processing stages to interpret serial dependence phenomena. These ongoing explorations are crucial for uncovering the mechanisms underlying dynamic visual processing and understanding how the visual system encodes, represents stimuli, and makes decisions.

Several competing mainstream perspectives currently exist regarding serial dependence mechanisms: One view holds that serial dependence is a perceptual-level effect occurring before sensory signals are transformed into conscious representations. Specifically, perceptual processing of previous stimuli distorts the sensory encoding of subsequent stimuli, thereby warping the perceptual appearance of visual stimuli (Cicchini et al., 2014; Fischer & Whitney, 2014; St John-Saaltink et al., 2016). A second perspective suggests that although serial dependence acts at the perceptual level of current stimuli, this process is regulated by feedback signals from higher-level neural areas (Fornaciai & Park, 2019b). Another view attributes serial dependence to dynamic biases in working memory (Bliss et al., 2017; Fritsche et al., 2017). Some researchers argue that serial dependence originates from decision-making processes. For example, the "decision template" theory proposes that serial dependence arises from how previous trial decisions influence current trial decisions (Ceylan et al., 2021; Fritsche et al., 2017; Pascucci et al., 2019). Finally, some scholars suggest that serial dependence may exist across multiple cognitive processing stages rather than having a single mechanism (Pascucci et al., 2019). Below, we detail the experimental evidence and controversies surrounding these perspectives.

4.1 Perception-Based Serial Dependence: The Continuity Field

Fischer and Whitney (2014) proposed the "continuity field" as the first theoretical explanation for serial dependence origins. This account builds directly on previous research investigating the spatiotemporal tuning properties of serial dependence. As early as 2011, researchers discovered an effect similar to serial dependence. Specifically, Corbett et al. (2011) used an n-back paradigm and found that estimates of repeated stimuli were significantly biased toward the same stimulus presented previously. This effect' s magnitude decreased with increasing intervals between the two stimuli and was stronger within the same visual field region, suggesting spatiotemporal tuning properties. Fischer and Whitney (2014) further provided more systematic and comprehensive experimental evidence for spatial tuning using Gabor stimuli—serial dependence magnitude decreased with increasing spatial distance between consecutive stimuli, reaching maximum when locations overlapped. Numerous subsequent studies have also revealed temporal tuning—when spatial location is fixed, serial dependence decreases with increasing temporal intervals between stimuli (Fritsche et al., 2017). Regarding temporal tuning, research shows that the previous 2-3 trials can exert attractive influences on the current trial (Cicchini et al., 2017; Kalm & Norris, 2018), and this temporal tuning is robust against interference—even when other tasks are inserted between trials, the attractive influence persists across the intervening task to affect the current trial (Fritsche, Mostert & de Lange, 2017). Summarizing these findings, serial dependence can extend across a relatively large temporal window (10-15 seconds) and spatial range (approximately 20° visual angle) (Fischer & Whitney, 2014; Liberman et al., 2014; Manassi et al., 2017). Fischer and Whitney (2014) termed this spatiotemporal tuning region the "continuity field" and used it to explain serial dependence origins. According to this theory, the continuity field is a spatiotemporal tuning operator that gradually integrates representations of spatially proximal stimuli over time. Within this specific spatiotemporal range (the continuity field), stimulus representations integrate across spatial and temporal dimensions. This integration' s essence is that within the continuity field, previous sensory input alters the default encoding properties of sensory neurons, thereby distorting current sensory encoding and causing current stimulus representations to drift toward previous encoding directions—producing serial dependence.

Beyond spatiotemporal tuning, substantial evidence supports the continuity field theory. First, stimulus similarity influences serial dependence, with numerous findings showing stronger effects among similar, continuous stimuli. This is well-explained by perceptual effects: similar stimuli are more likely to undergo perceptual integration, leading to response bias. Second, studies have found that serial dependence persists even without behavioral responses (Fornaciai & Park, 2018a). Particularly, researchers have cleverly separated behavioral responses from perceptual encoding. After excluding response and decision influences, they found serial dependence can occur purely based on perception—regardless of whether response methods differ across trials (Cicchini et al., 2017; Rafiei et al., 2021) or whether behavioral responses occur or are correct (St John-Saaltink et al., 2016). Moreover, importantly, what causes serial dependence is not the previous stimulus input itself but our perception of the previous stimulus (St John-Saaltink et al., 2016; Zhang & Alais, 2020), further highlighting the importance of perceptual components in serial dependence.

4.2 Conditional Perception-Based Serial Dependence: Contributions of High-Level Neural Feedback

Although the processing stage of serial dependence generation remains controversial, evidence for its existence at the perceptual stage is undeniable. This evidence points in two possible directions: one is that serial dependence is a purely perceptual-stage process, as described by continuity field theory; the other is that although serial dependence ultimately acts at the perceptual stage, this process is regulated by feedback signals from higher-level neural areas (Fornaciai & Park, 2019b)—that is, perception-based serial dependence is "conditional" and cannot be separated from higher-level feedback information.

Fornaciai and Park (2019b) used backward masking to suppress feedback signals from high-level processing to early perception. Their results showed that serial dependence could not be generated under these conditions, indicating that serial dependence requires not only visual perception but also feedback signals from higher brain areas to visual perception (Fornaciai & Park, 2019b). Cicchini et al. (2021) provided converging evidence from another angle. They found that serial dependence originates from high-level representational results of previous stimuli acting via feedback on early (rather than late) sensory processing stages of current stimuli. In other words, post-perceptual high-level processing of the previous stimulus influences early perceptual processing of the current stimulus. Researchers have yet to reach clear conclusions about whether serial dependence is based on "pure" or "conditional" perception. However, a noteworthy research direction is that conditional perception-based serial dependence further decomposes the origin question into two aspects—source and site of action corresponding to different cognitive processing stages. This recent approach proposes a more refined method for explaining serial dependence mechanisms: whether it originates in the perceptual or post-perceptual stage of the previous stimulus, and whether it influences early or late processing of the current stimulus.

4.3 Post-Perceptual Processing-Based Serial Dependence

In recent years, increasingly many characteristics of serial dependence have emerged that cannot be explained by "perceptual effects." First, attractive serial dependence is modulated by feature-based attention (Fritsche & de Lange, 2019), indicating it is not merely a low-level perceptual phenomenon. Second, binocular paradigms show that serial dependence occurs after binocular stimulus combination (Fornaciai & Park, 2018b; Kim et al., 2020), not at early perceptual stages. Third, recent experimental evidence indicates that serial dependence is not just a perceptual effect but occurs at later processing stages after stimulus features have been integrated. For example, Ceylan et al. (2021) found that orientation-based serial dependence can occur across spatial frequencies and even across stimulus types; Fornaciai and Park (2019a) found numerosity-based serial dependence can occur across stimulus formats; and Liberman et al. (2014) found face identity-based serial dependence can occur across viewpoints (indicating the effect is independent of low-level visual features and operates at a higher-level "identity" representation). Fourth, recent studies controlling decision variables have found that serial dependence requires post-perceptual processing such as decision-making—perceptual encoding alone is insufficient (Bae & Luck, 2020; Pascucci & Plomp, 2021). Finally, the coexistence of attractive serial dependence and repulsive negative aftereffects (Bliss et al., 2017; Czoschke et al., 2019), and their dissociation in spatiotemporal tuning and attentional modulation, cannot be simultaneously accommodated by continuity field theory. Experimental evidence from attentional modulation, binocular competition, processing integration, decision dependence, and repulsive effects all support the view that serial dependence originates from higher-level post-perceptual processing stages. Researchers have subsequently discovered that post-perceptual working memory and decision-making stages play important roles in serial dependence, leading to post-perceptual models based on working memory and decision-making.

4.3.1 Working Memory Bias-Based Serial Dependence Many previous serial dependence studies did not exclude working memory involvement. Some studies found that extending the interval between current stimulus and behavioral response enhanced serial dependence, suggesting that the effect operates at late cognitive processing stages of working memory (rather than early perception). More specifically, dynamic biases in working memory may be the potential source of bias in serial dependence (Bliss et al., 2017; Fritsche et al., 2017; Papadimitriou et al., 2017). When response time was zero—i.e., no working memory representation maintenance—attractive serial dependence did not occur, and repulsive negative aftereffects appeared instead (Bliss et al., 2017). However, conclusions from extended response time paradigms remain debatable. Manassi et al. (2018) proposed that the repulsive negative aftereffects obtained by Bliss et al. under zero-delay immediate response conditions resulted from excessively high stimulus contrast making targets too salient. When replicating Bliss et al.' s experiment with low-contrast (4% Michelson contrast) grating stimuli, they obtained attractive serial dependence effects. Accordingly, Manassi et al. (2018) argued that the key factor determining history effect direction and magnitude in this paradigm is luminance contrast (or uncertainty more generally), not delay time itself.

A recent study provides new insights into whether serial dependence is based on working memory bias. Unlike traditional paradigms, Fornaciai and Park (2020a) required participants to simultaneously memorize three stimulus frames and tested whether memory interference is a sufficient condition for generating serial dependence. They found serial dependence effects based entirely on memory interference that were bidirectional (for a series of stimuli stored in memory, serial dependence need not be the traditional forward influence from the previous stimulus to the subsequent one; later stimuli can also bias processing of earlier stimuli). Overall, this study provides strong experimental evidence for working memory bias-based serial dependence.

4.3.2 Decision Template-Based Serial Dependence In a recent study, Ceylan et al. (2021) proposed a decision-based serial dependence model—serial dependence is a bias occurring at a relatively high-level decision stage. Previous stimuli influence the decoding of sensory activity for current stimuli by altering the readout from "decision" units (a set of weights used to form final perceptual representations from low-level sensory neuron population activity). In other words, traces of past perceptual decisions ("decision templates") are altered by decision-making about previous stimuli, thereby modulating perceptual representations of current stimuli.

Consistent with the decision template theory, when decision-making is incorporated as a variable in serial dependence analyses, studies find that decisions about stimuli are more effective predictors than the stimuli themselves (Pascucci et al., 2019; St John-Saaltink et al., 2016). Some studies have cleverly separated contributions of stimuli, decisions, and behavioral responses through experimental design and data analysis, finding that both stimuli and decisions produce stable serial dependence effects (Cicchini et al., 2017; Frund et al., 2014). However, serial dependence purely from behavioral responses has not been consistently confirmed, with some studies finding that behavioral responses actually produce repulsive negative aftereffects (Zhang & Alais, 2020).

4.4 Perception-Decision Cascade-Based Serial Dependence

Experimental evidence from different processing stages has led researchers to realize that serial dependence may not be a single-mechanism phenomenon or a byproduct of a single neural process, but rather likely originates from multiple processing stages with multiple components. Pascucci et al. (2019) proposed a perception-decision cascade theory of serial dependence. This theory emphasizes that repulsive negative aftereffects similar to adaptation phenomena occur at early perceptual levels based on population coding of sensory neurons, while attractive serial dependence occurs at later decision levels based on decision templates influencing decoding of current stimulus sensory activity. Although these two effects have distinct functional mechanisms operating at different processing stages, they are sequentially integrated (concatenated) to form a hierarchical structure of serial dependence. Therefore, this theory is also called the two-process model of serial dependence. Researchers have proposed that these two components may serve completely different functions: repulsive negative aftereffects focus on perceptual "segregation" to help vision more sensitively capture input changes and maintain perceptual independence and detail of objects (Sharp et al., 2019), whereas attractive serial dependence focuses on "integration" of temporally and spatially proximal inputs to reduce noise (Cicchini et al., 2017).

4.5 Neurophysiological Studies of Serial Dependence

Most current research on serial dependence cognitive mechanisms is speculative based on behavioral results. Existing theoretical perspectives and cognitive models require further corroboration from cognitive neuroscience evidence. In recent years, researchers have approached serial dependence from its neural mechanisms, providing direct evidence from neural signals at different processing stages for some cognitive models.

First, EEG studies provide evidence for perception-based serial dependence. For example, Fornaciai and Park (2018a) had participants passively view numerosity stimuli and analyzed visual evoked potentials elicited by different numerosities. Their results showed that even without explicit tasks or behavioral relevance, the magnitude of previous stimuli systematically biased current stimuli in an attractive manner. This influence cannot be attributed to decision processes and can only be explained by perceptual-level bias. Additionally, EEG studies have found that brain electrophysiological responses influenced by previous stimuli appear early in stimulus processing, indicating that serial dependence begins at early perceptual stages (Fornaciai & Park, 2018a, 2020b). Similarly, St John-Saaltink et al. (2016) used fMRI to record visual cortex activity patterns while participants performed orientation forced-choice tasks and found attractive biases imposed by previous perception at early sensory representation levels.

Second, some studies (Trapp et al., 2021; Pascucci et al., 2019) explain serial dependence neural mechanisms from the perspective of synaptic plasticity. For example, Pascucci et al. (2019) propose that the neural basis of the two-process model lies in a functionally distinct two-layer neural network: an input layer where neurons selectively encode basic visual attributes through population coding, and a readout layer where neurons decode signals from the input layer. Due to short-term plasticity and slowly decaying weights in synaptic connections between the two layers, inertia characteristics emerge in the decoding of sequential sensory signals—producing serial dependence. The neurophysiological basis of such serial dependence is temporary synaptic traces caused by recent events (including previous stimuli and related decisions). This explanation aligns with synaptic plasticity accounts of decision-making in neurophysiological research (Wang, 2008).

Furthermore, some studies provide cognitive neuroscience evidence for short-term/working memory interference-based serial dependence. Fornaciai and Park (2020b) used "activity-silent" working memory reactivation techniques and neural decoding analysis to find that neural activity from previous trials can be stored and maintained for relatively long periods after perception; new sensory pulses in current trials can "reignite" past neural activity in a silent state and act on current sensory information processing in an "echo" -like manner. Stein et al. (2020) found that two types of brain damage patients (anti-NMDAR encephalitis and schizophrenia) showed significantly reduced working memory-based serial dependence compared to healthy individuals, despite having intact working memory precision. In another recent study, de Azevedo Neto and Bartels (2021) applied transcranial magnetic stimulation (TMS) noise to dorsal premotor cortex during inter-trial intervals without any task. They found that this interference did not reduce visuomotor performance across trials but significantly decreased inter-trial serial dependence magnitude. This suggests that in the visuomotor task used, premotor areas are involved in transferring previous trial information into memory modules, and stored previous trial information is an important source of serial dependence. Overall, these studies indicate that serial dependence is closely related to short-term/working memory.

5. Adaptive Significance and Mathematical Modeling of Serial Dependence

Due to head and eye movements, object occlusion, lighting changes, and other factors, visual input is typically noisy, dynamic, and unstable, yet our subjective visual perception maintains uninterrupted stability. Since its proposal, serial dependence has been considered a mechanism for achieving visual processing stability by integrating visual input along the temporal dimension to promote stability (Cicchini et al., 2014; Fischer & Whitney, 2014). Despite diverse theoretical explanations for serial dependence mechanisms, its final behavioral outcome—biasing influence between consecutive stimuli—indeed maintains stability and continuity in visual processing. This stability and continuity also establish direct connections between serial dependence and other visual processes. For example, research shows that when occluders are present in the visual field, serial dependence helps enhance object stability and continuity in motion processing (Liberman et al., 2016). Face-related studies also demonstrate that serial dependence aids identity recognition ability (Turbett et al., 2019) and emotion perception ability (Mei et al., 2019). From an evolutionary perspective, the function of serial dependence is adaptive to environmental demands. Visual input at successive moments is typically very similar (Liberman et al., 2016), and natural visual statistics are dominated by slowly changing components (Ruderman & Bialek, 1994). Therefore, weighted averaging combining current and historical stimulus perceptions effectively reduces noise components in sensory input to maintain perceptual stability and conserve cognitive resources.

In recent years, researchers have investigated the adaptive significance of serial dependence (including smoothing visual noise, conserving perceptual resources, and even speeding responses) through mathematical modeling. For example, Kalm & Norris (2018) and Cicchini et al. (2017, 2018) used Bayesian models to mathematically model serial dependence. According to Bayesian models, observers continuously revise predictions about visual input changes by integrating current sensory input with prior knowledge obtained from long-term experience. Kalm and Norris (2018) verified the importance of prior knowledge in this process through model fitting of psychophysical data. They found that compared to filter models considering only current data or natural prior models combining a single previous trial with current data, a mixture model incorporating information from multiple previous trials best fit serial dependence characteristics. Cicchini et al. (2017, 2018) used an "ideal-observer model" to model experimental data, finding that the weighting of past information increased with sensory noise of average stimuli and was inversely proportional to differences between past and current stimuli. These Bayesian model-based findings align with predictive coding theory (Huang & Rao, 2011). According to predictive coding theory, at every neural stage, encoding of the previous stimulus (as prior experience) exerts "predictive" influence on encoding of the next stimulus, and neural responses ultimately reflect the combined result of multiple stages (Huang & Rao, 2011). Therefore, predictive coding theory may provide further expansion of ideas for mathematical modeling of serial dependence reflected across multiple cognitive processing stages (Cicchini et al., 2021). Additionally, Cicchini et al.' s (2018) mathematical modeling predicted that when serial dependence increases, not only should errors in stimulus reproduction tasks decrease, but reaction times should also speed up. However, reaction time speeding in serial dependence has not been captured by most experimental studies, and the specific reasons require further investigation.

6. Summary and Future Directions

In summary, research on serial dependence has made considerable progress: researchers have discovered this effect across various levels of visual processing (from low-level features like orientation, spatial location, and numerosity to high-level attributes like identity, attractiveness, and aesthetic value). The effect has distinct characteristics differentiating it from other history effects and is influenced by numerous factors including attentional modulation, stimulus feature modulation, sensory uncertainty modulation, and spatiotemporal tuning properties. Its origins are remarkably complex (including sensory encoding, high-level cortical feedback modulation, working memory, decision templates, perception-decision cascades, etc.), reflecting projections of past processing traces onto current cognition from different hierarchical levels. However, current research on serial dependence still has substantial room for expansion, and future studies could develop in the following directions.

First, multiple approaches should be combined to resolve the origin question of serial dependence. The origin of serial dependence remains unclear, with evidence existing for perception, memory, decision-making, and response stages. Exploring this core issue remains the primary task for future research. Researchers may need to make breakthroughs in two aspects.

On one hand, innovative experimental paradigms and data analysis methods are needed to further separate different cognitive processing stages. In typical perceptual paradigms, perception, decision-making, and responses are often confounded. Although experimental controls can achieve some separation—for example, St John-Saaltink et al. (2016) titrated response accuracy to separate perception and decision-making within trials, and Cicchini et al. (2017) used a completely different approach to separate perception and decision-making—these separations are often incomplete, typically isolating only one process or merely reducing involvement of a particular process. Future research needs to widely borrow and employ clever methods and mature paradigms from other fields to achieve complete separation of cognitive processing stages and explore serial dependence origins. Recent relevant attempts deserve attention, including Cicchini et al. (2021) using visual illusions to investigate serial dependence sources and stages of action; Rafiei et al. (2021) using visual search paradigms to separate effects of attended and unattended stimuli; and two studies (Fornaciai & Park, 2018b; Kim et al., 2020) using binocular rivalry paradigms to investigate serial dependence occurrence stages.

On the other hand, future research urgently needs to combine cognitive neuroscience techniques to obtain critical experimental evidence regarding serial dependence origins. Although researchers have made some progress on neural mechanisms—for example, Fornaciai and Park (2018a) using visual evoked potentials (VEP), St John-Saaltink et al. (2016) using fMRI, and Papadimitriou et al. (2017) using single-cell activity recordings to investigate neural bases of serial dependence—the proportion of studies using cognitive neuroscience techniques remains very small. The vast majority of studies employ behavioral and psychophysical methods and thus cannot provide direct neural-level evidence for issues such as serial dependence origins and characteristics of different processing stages, nor can they address questions that behavioral experiments cannot resolve, such as the developmental and evolutionary timeline of serial dependence across different cognitive processing stages.

Second, research should deeply expand the influencing factors of serial dependence and achieve refined experimental manipulation. As serial dependence research grows, researchers have discovered increasing variables that affect the effect. Beyond widely studied factors like attention and spatiotemporal tuning, these include stimulus range, stimulus uncertainty, static and dynamic stimulus characteristics, attentional control, and participant confidence. How these factors influence serial dependence requires more detailed investigation. For example, Collins (2019) built upon previous research on spatial location modulation of serial dependence and further revealed that this modulation is based on retinotopic coordinates (i.e., relative positions where stimuli project onto the retina) rather than external spatial coordinates (i.e., absolute positions in external space). Similar expandable questions include: To which stimulus types can serial dependence generalize? What are the specific temporal and spatial tuning ranges for serial dependence with different stimulus types? At what magnitude of stimulus difference does serial dependence transition to short-term repulsive adaptation effects? What are the commonalities and differences between object-based and feature-based attentional influences on serial dependence?

Third, further exploration of individual differences in serial dependence is needed. Previous studies have yielded inconsistent results regarding whether individual differences exist in serial dependence. Some perceptual decision-making studies have observed significant individual differences in serial dependence magnitude, breadth, and even direction (Braun et al., 2018; Frund et al., 2014), while other studies have found relatively consistent results across participants (Fischer & Whitney, 2014). If individual differences in these studies stem from experimental control, this implies that future research must be more careful with experimental controls, precisely manipulating known variables that modulate serial dependence (e.g., choice of spatial coordinate system, stimulus contrast, spatial position differences) and considering additional unknown factors. On the other hand, if individual differences are not limited to experimental control, studying these differences could open a window for deeply understanding serial dependence mechanisms and functions. For example, research at the individual level has found that the magnitude of face identity-based serial dependence significantly correlates with individuals' face identity recognition abilities, indicating that serial dependence widely participates in human face encoding and recognition (Turbett et al., 2019; Turbett et al., 2021).

Fourth, the impact of serial dependence on psychological experimental design must be 高度重视. From a methodological perspective, the discovery of serial dependence brings the following implications and insights: any future psychological experimental design involving sequential stimuli must consider the potential influence of serial dependence between consecutive stimuli. The temporal span here is broad, ranging from hundreds of milliseconds within the same trial (Fornaciai & Park, 2019a) to several seconds between adjacent trials (Ceylan, Herzog & Pascucci, 2021). Therefore, on one hand, in future experimental paradigm design and result interpretation, researchers must treat serial dependence as an important variable—alongside priming and adaptation—that may affect experimental validity and interpretation, implementing appropriate controls and necessary discussions. On the other hand, given that serial dependence widely exists across visual processing levels (from low-level features like orientation, spatial location, and numerosity to high-level attributes like identity, attractiveness, and aesthetic value), its presence and role in numerous previous psychological paradigms involving sequential stimulus processing (e.g., aesthetic judgment, face recognition, numerosity identification, and arithmetic operations) warrant reconsideration and necessary retrospective investigation.

Serial dependence effect —A novel "history effect"

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Abstract: A novel "History effect", i.e., the Serial Dependence Effect (SDE), was introduced into vision research since 2014. The SDE is an attractive bias in cognitive processing, referring to the phenomenon that the representation of a current stimulus is pulled toward the stimuli presented moments ago. Serial dependence has been observed in many substrates of visual processing, spanning from low-level features, such as orientation, spatial location, and numerosity, to high-level attributes, such as identity, attractiveness, and aesthetic judgment. Recent studies have revealed profound origins for this effect, including sensory coding, feedback regulation of high-level cortex, working memory, decision template, cascade of perception and decision, etc., which reflect projections of recent processing traces to current cognition from different levels. Abundant progress has been made on typical characteristics, modulating factors, cognitive and neural mechanisms, and theoretical explanations of the serial dependence effect. However, there are still many contradictions and ongoing debates that need to

be explored and clarified by future researches.

Key words: Serial dependence effect, cognitive and neural mechanisms, perception, memory, decision;

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