Spatial Generalization of Serial Dependence Effects in Visual Duration Perception

Authors: Wang Biyao, Chen Chen, Hu Xiaofei, Wang Di, Li Baolin, Li Baolin

Date: 2023-12-05T00:00:00+00:00

Abstract

An individual's current perceptual response depends not only on the current stimulus input but also on prior perceptual experience, which can manifest as perceptual serial dependence effects. Using a temporal bisection task, we systematically manipulated the spatial relationship between stimuli in previous and current trials across three experiments to investigate the serial dependence effect in duration perception and its spatial transferability. The results revealed that (1) the stimulus duration in previous trials induced a repulsive stimulus serial dependence effect, and this effect could be completely transferred to different spatial locations; (2) the decision response in previous trials induced an attractive decision serial dependence effect, but this effect could only be partially transferred to different spatial locations; (3) the spatial transferability of both stimulus and decision serial dependence effects in duration perception was not modulated by spatial type (external space vs. retinal space). These findings partially reflect the potential neural loci underlying serial dependence effects in visual duration perception: the stimulus serial dependence effect may arise from higher-level visual processing brain regions that are insensitive to spatial information or possess large receptive fields; the decision serial dependence effect may originate from higher-level cognitive brain regions with categorical organization functions.

Full Text

Preamble

Spatial Generalization of Serial Dependence in Visual Duration Perception

WANG Biyao[1], CHEN Chen[1], HU Xiaofei[1], WANG Di[1], LI Baolin[1]
([1] School of Psychology, Shaanxi Normal University, Xi'an 710062)

Abstract

Perceptual responses are shaped not only by current sensory input but also by prior perceptual experience, a phenomenon known as serial dependence in perception. Using a duration bisection task, three experiments systematically manipulated the spatial relationship between stimuli in previous and current trials to investigate serial dependence in duration perception and its spatial generalization. The results revealed that: (1) previous stimulus duration produced a repulsive stimulus serial dependence effect that fully transferred across different spatial locations; (2) previous decision responses generated an attractive decisional serial dependence effect that only partially transferred across spatial locations; and (3) the spatial generalization of both stimulus and decisional serial dependence effects was not modulated by spatial type (external space vs. retinal space). These findings suggest distinct neural loci for visual duration perception serial dependence: stimulus serial dependence likely originates in higher-level visual processing areas insensitive to spatial information or with large receptive fields, whereas decisional serial dependence may arise from higher cognitive areas with categorical organization functions.

Keywords: duration perception, serial dependence effect, duration adaptation, decision inertia, spatial generalization
Classification Code: B842.2

Duration perception refers to the perception of event duration, including the perception of how long an event lasts or the interval between two successive events (Huang et al., 2003). As a crucial component of time perception, duration perception forms the basis for individual interaction with the external environment and is essential for survival and development. Everyday activities such as speaking, playing music, driving, and sports all require duration perception. However, subjective duration is not solely determined by objective physical time; it can be distorted by multiple factors (Matthews & Meck, 2016). For example, repeated presentation of a relatively long (or short) duration leads participants to perceive subsequent intermediate durations as shorter (or longer) than in a non-adaptation condition, producing duration aftereffects (Heron et al., 2012; Li, Yuan, & Huang, 2015). This demonstrates that perceptual history is an important factor influencing duration perception.

The influence of perceptual history on duration perception manifests not only in long-term adaptation phenomena but also in serial dependence effects. Serial dependence refers to the influence of previous trials on current perception, reflecting the impact of short-term prior experience on subsequent perceptual processing. Information from previous trials is complex and multidimensional. In typical perceptual judgment tasks, previous trial information includes both previous stimulus information and previous decision information. Accordingly, serial dependence effects can be divided into at least two categories: (1) the effect of previous stimulus information on current perceptual processing, known as the stimulus serial dependence effect; and (2) the effect of previous decision responses on current perceptual processing, known as the decisional serial dependence effect. Serial dependence has been shown to be a ubiquitous phenomenon, occurring not only in low-level information processing such as orientation (Fischer & Whitney, 2014; Pascucci et al., 2019), numerosity (Michele & Joonkoo, 2018), and motion (Fischer et al., 2020), but also in high-level face processing (Liberman et al., 2014).

Recent research has begun to examine serial dependence in duration perception. For example, Wiener et al. (2014) used a duration bisection task in which participants classified each test stimulus duration as “longer” or “shorter.” They found that current duration judgments were simultaneously influenced by both previous stimulus duration and previous decision information: when the previous stimulus duration was long (or short), participants tended to judge the current stimulus as shorter (or longer); when the previous decision was “longer” (or “shorter”), participants tended to judge the current stimulus as longer (or shorter). This indicates that previous stimulus duration information produces a repulsive effect in duration perception, whereas previous decision information produces an attractive effect. Similar findings in other perceptual domains suggest that previous stimuli and previous decisions exert opposite influences on current perceptual processing: previous stimulus information causes repulsive effects, shifting current perceptual decisions away from previous stimuli, whereas previous decision information causes attractive effects, biasing current decisions toward repetition of previous choices (Feigin & Shalom-Sperber et al., 2021; Pascucci et al., 2019).

However, previous studies have only found stimulus serial dependence effects in the auditory modality, while decisional serial dependence effects have been observed in both visual and auditory modalities (Wehrman et al., 2020; Wiener et al., 2014). This pattern may be related to the analytical methods used in previous research. To investigate the effects of previous stimulus duration and decision responses on current duration perception, prior studies typically categorized current trials based on previous stimulus duration or decision type. For example, to examine the effect of previous decisions, researchers classified current trials into two categories corresponding to previous “longer” or “shorter” decisions, then used traditional psychophysical methods to compute and compare duration perception performance across these categories (Wiener et al., 2014). However, a critical issue is that previous stimulus duration and previous decision responses are closely correlated: objectively longer durations are more likely to be judged as “longer,” and vice versa. Therefore, this analytical approach cannot completely dissociate the independent contributions of previous stimulus duration and previous decision responses to subsequent duration perception (with possible effect confounding or cancellation). This may explain why stimulus serial dependence effects were not observed in the visual modality: the effects of stimulus and decisional serial dependence may be opposite in direction (repulsive vs. attractive), and decisional serial dependence may be stronger in vision, weakening or even canceling out stimulus serial dependence.

To address this limitation, a recent study used a probabilistic choice model to simultaneously incorporate previous stimulus duration and previous decision information to predict current duration judgments. The results revealed significant repulsive effects of previous stimulus duration and significant attractive effects of previous decisions in both visual and auditory modalities (Li et al., 2023). This demonstrates that similar stimulus and decisional serial dependence effects exist in duration perception across both modalities.

Research has shown that repulsive stimulus serial dependence effects are essentially similar to sensory adaptation aftereffects (Moon & Kwon, 2022). Prior studies on stimulus serial dependence in duration perception support this view. For instance, research has found that stimulus serial dependence in duration perception is modality-specific (Li et al., 2023), similar to the repulsive duration aftereffects produced by long-term duration adaptation (Heron et al., 2012). However, the neural locus of visual duration perception stimulus serial dependence remains unclear. Although fMRI studies have found that (long-term) visual duration adaptation aftereffects may originate in the right parietal lobe (Hayashi & Ivry, 2020), this does not necessarily mean that stimulus serial dependence also originates in this region. Unlike aftereffects produced by long-term adaptation, stimulus serial dependence reflects the influence of short-term prior stimuli on current perceptual processing, representing a rapid adaptation mechanism. Previous research has shown that adaptation duration is an important factor influencing neural adaptation in different brain regions (Fang et al., 2005). Therefore, the neural mechanisms underlying long-term and rapid adaptation may differ. Indeed, studies on auditory stimulus serial dependence have found that it is not constrained by sound frequency (Li et al., 2023), contrary to the characteristics of auditory duration aftereffects produced by long-term adaptation (Li, Yuan, & Huang, 2015), suggesting that long-term and rapid auditory duration adaptation mechanisms are distinct. In summary, further investigation of the underlying mechanisms of visual duration perception stimulus serial dependence is warranted.

The mechanisms underlying decisional serial dependence in duration perception also remain debated. Research has found that decisional serial dependence in duration perception is constrained to varying degrees by sensory modality and within-modality stimulus features (e.g., topological shape and sound frequency) (Li et al., 2023). Given that decision-making is a high-level cognitive process, the researchers proposed that the constraints of stimulus features on decisional serial dependence may originate from categorical organization mechanisms in higher cognitive brain regions. However, such constraints also align with information processing characteristics of early sensory cortex. Therefore, decisional serial dependence in duration perception may also reflect the influence of previous decision information on early sensory cortex processing through feedback mechanisms. Using visual surround tilt illusion, Cicchini et al. (2021) investigated orientation serial dependence and found that when previous trials were illusory and current trials were neutral, the attractive serial dependence effect depended primarily on previous perceived (rather than physical) orientation, indicating that previous information influences current perception after incorporating previous visual illusions. Conversely, when previous trials were neutral and current trials were illusory, the serial dependence effect depended primarily on current physical (rather than perceived) orientation, suggesting that the interaction between previous and current information occurs before visual illusion processing. This pattern indicates that previous information can directly affect low-level sensory processing in early visual cortex. Additionally, fMRI research has found that attractive serial dependence effects in orientation perception can be represented by neural activity in primary visual cortex (V1), and both behavioral and neural serial dependence effects exhibit some spatial specificity (St John-Saaltink et al., 2016). This again suggests that attractive serial dependence effects may involve early visual cortex. Moreover, considering that early visual cortex (such as V1) plays an important role in visual duration processing (Shuler, 2016), it is worth considering whether early visual cortex is involved in generating attractive decisional serial dependence in duration perception.

To reveal the potential neural loci of visual duration perception serial dependence, this study investigated its spatial generalization characteristics. Cognitive neuroscience research has shown that visual neurons have unique receptive fields, with adjacent neurons having adjacent receptive fields in visual cortex. This point-to-point mapping between visual cortex and retinal space is known as retinotopic mapping (Wandell et al., 2007). Furthermore, receptive fields of neurons at different levels of the visual pathway differ, generally increasing in size with higher visual hierarchy (Amano et al., 2009; Harvey & Dumoulin, 2011). For example, at 5.5° eccentricity, receptive fields in V1 are typically smaller than 2°, V2 receptive fields range from 2° to 4°, V4 receptive fields range from 4° to 6°, while higher-level posterior inferior temporal cortex (TEO) receptive fields exceed 6° (Kastner et al., 2001). Additionally, some high-level visual areas (such as ventral intraparietal area, VIP) have receptive fields not fixed to specific retinal locations but responsive to fixed locations in external space, exhibiting spatiotopic mapping (Duhamel et al., 1997). These characteristics of receptive fields in different visual cortical areas provide important inferential basis for understanding the neural loci of corresponding visual representations. Leveraging these features, numerous studies have investigated the spatial generalization characteristics of visual effects to reveal their potential neural origins. For example, Knapen et al. (2010) found that retinal position critically constrains tilt aftereffects, leading to the inference that tilt aftereffects originate in early visual cortex (such as V1) sensitive to retinal position. Burr et al. (2007) found that duration compression effects caused by visual motion adaptation depend on the consistency of external (rather than retinal) spatial positions of adaptation and test stimuli, suggesting that this effect originates in higher-level brain regions (such as parietal cortex) rather than early visual cortex. Therefore, investigating the spatial generalization of serial dependence in duration perception can help further understand its potential neural locus. It can be hypothesized that if serial dependence in duration perception originates in early visual cortex (such as V1) with strict retinotopic mapping, it will exhibit retinotopic spatial specificity.

Moreover, investigating the spatial generalization of serial dependence in duration perception has practical significance. Previous studies have only examined serial dependence in duration perception under single spatial contexts (Li et al., 2023; Wehrman et al., 2020; Wiener et al., 2014), which limits the ecological validity of the findings. Real-world environments are rich and diverse, with objects constantly changing positions due to object motion and observer movement. Therefore, examining the spatial generalization of serial dependence in duration perception helps us understand how previous duration perception experience influences subsequent duration perception in more complex real-world environments. Previous investigations of spatial characteristics of serial dependence have focused primarily on the perception of spatial attributes of objects. Studies have shown that serial dependence effects in orientation perception (Fischer & Whitney, 2014) and image recognition (Manassi et al., 2019) are modulated by spatial position. However, unlike spatial information, duration information is highly abstract, and humans lack specialized receptors for processing duration information. Compared to spatial information, duration information processing involves unique cognitive and neural mechanisms (Merchant et al., 2013). Furthermore, previous investigations of spatial generalization in serial dependence for spatial attributes have not strictly distinguished between stimulus and decision influences (Fischer & Whitney, 2014; Manassi et al., 2019). Therefore, it is necessary to further investigate the spatial generalization of both stimulus and decisional serial dependence in duration perception.

In summary, this study employed a duration bisection task combined with a probabilistic choice model to investigate the spatial specificity/generalization of visual duration perception serial dependence through three experiments. Specifically, Experiment 1 examined the generalization of serial dependence between central and peripheral visual fields. Test stimuli were randomly presented in central and peripheral (10°) visual fields, and participants judged whether the current stimulus duration was “longer” or “shorter” than reference stimuli learned in a prior phase. Experiment 2 further investigated generalization across visual hemifields by randomly presenting stimuli in left and right visual fields (5°). Finally, Experiment 3 systematically varied fixation and stimulus positions to dissociate spatiotopic and retinotopic positions, further revealing the characteristics of spatial generalization in duration perception serial dependence. The results showed that both stimulus and decisional serial dependence effects in duration perception could transfer across different spatial positions, but the degree of transfer differed between the two effects. Moreover, the spatial generalization of these effects was not modulated by spatial type (external space vs. retinal space).

Experiment 1: Serial Dependence in Duration Perception Between Central and Peripheral Visual Fields

Experiment 1 investigated the manifestation and generalization of serial dependence in duration perception between central and peripheral visual fields. Visual processing capacity differs markedly between central and peripheral visual fields across numerous visual tasks (Rosenholtz, 2016; Strasburger et al., 2011). fMRI studies have also shown that stimuli at different visual eccentricities correspond to different neural representation locations in early visual cortex (Amano et al., 2009), and cortical magnification factor (CMF) decreases with increasing eccentricity (Qiu et al., 2006). This indicates that central vision has more important functional significance than peripheral vision. Therefore, if serial dependence in duration perception originates from early visual cortex processing, it should show different patterns in central and peripheral visual fields and should not transfer between them.

2.1.1 Participants

Using G*Power 3.1, we calculated that for a 2$×$2 repeated-measures ANOVA with significance level $\alpha = 0.05$ and medium effect size (f = 0.25), a sample size of 24 participants was required to achieve 80% statistical power (Faul et al., 2007). This sample size is comparable to previous related studies (Li et al., 2023; Wehrman et al., 2020). Therefore, Experiment 1 tested 24 university students (22 females; mean age M = 19.5 years, SD = 1.74 years). All participants were right-handed with normal or corrected-to-normal vision and remained naïve to the experimental purpose until debriefing. The study was approved by the ethics committee, and all participants provided written informed consent before the experiment and received monetary compensation afterward.

2.1.2 Stimuli and Apparatus

This experiment used visual stimuli. The visual stimulus was a white Gaussian blob (SD = 0.5°, Michelson contrast = 0.7) presented on the left or right side of a CRT monitor (refresh rate = 85 Hz, resolution = 1280$×$960 pixels) at 5° eccentricity. Throughout the experiment, participants sat approximately 58 cm from the monitor with their head stabilized by a chin rest. Stimulus presentation and data collection were controlled by experimental programs written in MATLAB using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

2.1.3 Design

A 2 (current stimulus position: central vs. peripheral visual field) × 2 (position consistency: consistent vs. inconsistent) within-subjects design was employed. The dependent variable was the proportion of trials in which participants judged the current test stimulus duration as longer than the reference stimulus.

Current stimulus position referred to the location of the test stimulus in the current trial, which could appear in either the central or peripheral visual field. Position consistency referred to whether the positions of test stimuli in the current and previous trials were the same: when both the current and previous test stimuli appeared in the central visual field or both appeared in the peripheral visual field, this constituted the position-consistent condition; when the current test stimulus appeared in the central visual field (or peripheral visual field) while the previous test stimulus appeared in the peripheral visual field (or central visual field), this constituted the position-inconsistent condition.

2.1.4 Procedure

The experiment employed a simplified duration bisection task (Wiener et al., 2014) (Figure 1 [Figure 1: see original paper]A). In each trial, a fixation point was presented for 500 ms, followed by a visual test stimulus randomly appearing at the fixation location or 10° to the right of fixation. The test stimulus duration was one of five durations ranging from 300 to 900 ms with equal logarithmic steps (i.e., 300, 395, 520, 684, or 900 ms). After stimulus offset, participants were instructed to respond as quickly as possible while maintaining accuracy, judging whether the test stimulus duration was "longer" or "shorter" than the remembered reference stimulus (see below). Response mapping was counterbalanced across participants: half pressed the "F" key with their left index finger for "longer" judgments and the "J" key with their right index finger for "shorter" judgments, while the other half used the opposite mapping. The fixation point was positioned 5° to the left of screen center, and participants were required to maintain fixation throughout the experiment. The stimulus presentation order was determined by a pseudo-random 103 de Bruijn sequence (Brimijoin & O'Neill, 2010), comprising 1000 trials total, with each duration presented 200 times (100 times per position condition). Participants took a short break (less than 30 s) after every 250 trials. Before the formal experiment, participants completed a learning task in which the reference stimulus (duration = 520 ms, the geometric mean of all test durations) was alternately presented at the fixation location and 10° to the right of fixation, five times each. During this phase, participants only needed to memorize the reference duration without making responses. If participants felt they had not yet memorized the reference duration, they could choose to repeat the learning phase until they felt confident, at which point they proceeded to the formal test phase. In the subsequent formal test phase, participants judged test stimulus durations based on their memory of the reference duration.

2.1.5 Data Analysis and Statistics

First, trials with reaction times exceeding three median absolute deviations (MADs) from each participant's median RT were excluded (Leys et al., 2013), resulting in the removal of 6.9% of trials. Next, to examine the effect of stimulus position on duration perception, we calculated for each participant the proportion of "longer" judgments for each duration and position condition. These data were fitted with cumulative Gaussian distributions using the psignifit Toolbox in MATLAB (see https://github.com/wichmann-lab/psignifit/wiki/; Schutt et al., 2016) to obtain each participant's point of subjective equality (PSE; the duration corresponding to 50% "longer" responses, representing the mean of the cumulative Gaussian distribution) and just noticeable difference (JND; half the difference between durations corresponding to 75% and 25% "longer" responses, reflecting temporal sensitivity, with smaller values indicating higher sensitivity) for each position condition. Based on these measures, we used paired-sample t-tests to examine the effects of stimulus position on duration perception accuracy (using the absolute difference between PSE and 520 ms, i.e., |PSE–520|, with smaller values indicating higher accuracy) and sensitivity (JND).

Previous studies typically compared PSEs across conditions to measure serial dependence in duration perception (Wehrman et al., 2020; Wiener et al., 2014). For example, Wiener et al. (2014) calculated stimulus serial dependence by first classifying trials into seven categories based on the seven previous stimulus durations, then using the slope of the linear fit of PSEs across these categories as the effect size. For decisional serial dependence, trials were classified into two categories based on previous decisions ("longer" or "shorter"), and the PSE difference between conditions with previous "shorter" versus "longer" responses was used as the effect size. However, for objectively longer (or shorter) test stimuli, participants are more likely to judge them as "longer" (or "shorter"), creating a strong correlation between responses and actual stimulus duration. Therefore, this analytical approach cannot completely dissociate the independent effects of previous stimulus duration and previous decisions on subsequent duration perception. To address this, we employed a probabilistic choice model for data analysis. This model can effectively separate the influences of different types of information from previous trials on current perceptual decisions and has been widely applied in serial dependence research across various perceptual phenomena (Feigin & Baror et al., 2021; Feigin & Shalom-Sperber et al., 2021). Specifically, the model predicts the proportion of trials in which participants judge the current test stimulus as "longer" using a binomial logistic regression function:

$$P(L)_t = \frac{1}{1 + e^{-x_t}}$$

where x_t is a linear combination of four predictor variables that may influence current perceptual decisions (see Figure 2 [Figure 2: see original paper]):

$$x_t = \beta_0 + \beta_{current\_stim} \cdot s_t + \beta_{prev\_stim} \cdot s_{t-1} + \beta_{prev\_choice} \cdot c_{t-1}$$

In this equation, s_t is the current stimulus duration; β_0 represents the baseline bias in making "longer" or "shorter" decisions; s_{t-1} is the previous trial's stimulus duration, with β_{prev_stim} as its weight; and c_{t-1} is the previous trial's decision response, with β_{prev_choice} as its weight. In this study, decision responses c_{t-1} had two categories ("longer" or "shorter," coded as +1 and –1), whereas stimulus duration s_t (300–900 ms) was a continuous variable changing in logarithmic steps. To make these parameters comparable, we converted stimulus durations to logarithmic form and standardized them using root-mean-square (RMS), following previous research (Feigin & Baror et al., 2021; Feigin & Shalom-Sperber et al., 2021). After this transformation, the RMS values of stimulus duration and decision response parameters were consistent (both equal to 1).

To quantify the influence of the four factors on current perceptual decisions, we constructed four comparison models. All models were based on the same logistic regression function but differed in their parameter types. Specifically, M_0 ("no-history" model) was the baseline model, assuming that current duration perception decisions were determined only by baseline bias and current stimulus duration information (i.e., setting β_{prev_stim} and β_{prev_choice} to 0 in Equation 2). M_1 ("stimulus-history" model) assumed that current decisions were determined by baseline bias, current stimulus duration, and previous stimulus duration (i.e., setting β_{prev_choice} to 0). M_2 ("choice-history" model) assumed that current decisions were determined by baseline bias, current stimulus duration, and previous decision information (i.e., setting β_{prev_stim} to 0). M_3 ("stimulus and choice history" model) assumed that current decisions were determined by all four factors: baseline bias, current stimulus duration, previous stimulus duration, and previous decision (i.e., all parameters in Equation 2 were non-zero).

Model comparison was performed using Akaike Information Criterion (AIC):

$$\mathrm{AIC} = -2\log L + 2k$$

where k represents the number of parameters in the model and L is its maximum likelihood estimate. After calculating AIC for each model for each participant, we computed the difference between the AIC of each history-containing model (M_1, M_2, M_3) and the baseline model (M_0): $\Delta\mathrm{AIC} = \mathrm{AIC}_{M_i} - \mathrm{AIC}_{M_0}$. Since smaller AIC values indicate better models, larger absolute ΔAIC values provide stronger evidence favoring the model with smaller AIC. Specifically, absolute ΔAIC values of 2–6, 6–10, or >10 indicate positive, strong, or very strong evidence, respectively, supporting the model with smaller AIC (Kass & Raftery, 1995).

To compute the effects of previous stimulus duration and decision information on current duration perception across different conditions, we divided trials into four groups: previous stimulus in central visual field and current stimulus in central visual field (CC); previous stimulus in peripheral visual field and current stimulus in peripheral visual field (PP); previous stimulus in peripheral visual field and current stimulus in central visual field (PC); and previous stimulus in central visual field and current stimulus in peripheral visual field (CP). The probabilistic choice model was applied separately to these four groups of data. Each group yielded four model coefficients (β_0, $\beta_{current\_stim}$, β_{prev_stim}, β_{prev_choice}). Among these, β_{prev_stim} and β_{prev_choice} reflect the influence of previous stimulus duration and decision information on current duration perception and are the focus of this study. The other two coefficients (β_0 and $\beta_{current\_stim}$) reflect baseline decision bias and the effect of current stimulus duration, respectively. Since these were not the focus, their results are presented in the Appendix (Figure S1).

For each model coefficient, we first used one-sample t-tests to determine whether it differed significantly from zero. Then, we conducted 2 (current stimulus position: central vs. peripheral visual field) × 2 (position consistency: consistent vs. inconsistent) repeated-measures ANOVAs to examine the effects of stimulus position and consistency on stimulus and decisional serial dependence and their spatial generalization.

2.2 Results

Figure 3 [Figure 3: see original paper]A shows psychometric functions for a representative participant in Experiment 1 across different spatial position conditions. At the group level, paired-sample t-tests revealed that duration perception accuracy (|PSE–520|) was significantly higher when stimuli were presented in the central visual field than in the peripheral visual field (59.68 ms vs. 130.37 ms, t(23) = –5.21, p < 0.001, Cohen's d = –1.06, 95% CI [–98.72, –42.64]) (Figure 3B). Additionally, JND was significantly smaller in the central visual field condition than in the peripheral visual field condition (114.82 ms vs. 137.67 ms, t(23) = 2.99, p = 0.007, Cohen's d = 0.61, 95% CI [7.02, 38.70]) (Figure 3C). This indicates that temporal sensitivity was higher and participants were more sensitive to changes in stimulus duration when stimuli were presented in central vision. These results confirm that stimulus position significantly affects duration perception.

To dissociate the effects of previous stimulus duration and previous decision responses on current duration perception, one-sample t-tests examined whether β_{prev_stim} coefficients differed from zero. Results showed that β_{prev_stim} was significantly less than zero in all four conditions (CC: t(23) = –4.88, p < 0.001, Cohen's d = –1.00, 95% CI [–1.28, –0.52]; PP: t(23) = –4.61, p < 0.001, Cohen's d = –0.94, 95% CI [–0.83, –0.32]; PC: t(23) = –5.57, p < 0.001, Cohen's d = –1.14, 95% CI [–0.96, –0.44]; CP: t(23) = –3.71, p = 0.001, Cohen's d = –0.76, 95% CI [–0.87, –0.25]) (Figure 4 [Figure 4: see original paper]A). Additionally, a 2 (current stimulus position: central vs. peripheral visual field) × 2 (position consistency: consistent vs. inconsistent) repeated-measures ANOVA revealed a marginally significant main effect of current stimulus position (F(1, 23) = 3.93, p = 0.060, $p^2 = 0.15$), while the main effect of position consistency (F(1, 23) = 0.69, p = 0.415) and the interaction (F(1, 23) = 0.83, p = 0.372) were not significant. These results demonstrate that previous stimulus duration information significantly influences current duration perception decisions, producing a repulsive effect that shifts current duration perception away from previous stimulus duration. Moreover, stimulus serial dependence in duration perception is not constrained by stimulus spatial position and can transfer between central and peripheral visual fields. Meanwhile, the effect tended to be weaker in peripheral than central visual field, indicating that the disadvantage of peripheral duration processing is also reflected in stimulus serial dependence.

One-sample t-tests on β_{prev_choice} coefficients revealed that the mean was significantly greater than zero in all four conditions (CC: t(23) = 12.82, $p < 0.001$, Cohen's d = 2.62, 95% CI [1.06, 1.47]; PP: t(23) = 17.49, $p < 0.001$, Cohen's d = 3.57, 95% CI [1.18, 1.50]; PC: t(23) = 3.08, p = 0.005, Cohen's d = 0.63, 95% CI [0.09, 0.47]; CP: t(23) = 4.22, $p < 0.001$, Cohen's d = 0.86, 95% CI [0.15, 0.45]) (Figure 4B). A repeated-measures ANOVA revealed a significant main effect of position consistency (F(1, 23) = 198.87, $p < 0.001$, $p^2 = 0.90$), with β_{prev_choice} coefficients significantly larger in position-consistent than inconsistent conditions. The main effect of current stimulus position (F(1, 23) = 0.54, p = 0.468) and the interaction (F(1, 23) = 0.34, p = 0.567) were not significant. These results indicate that previous decision information produces an attractive effect, biasing current perceptual decisions toward previous choices. Although this effect appeared across conditions, stimulus position consistency significantly modulated its magnitude, suggesting incomplete transfer across positions.

Finally, model comparison results showed that in position-consistent conditions, ΔAIC values were clearly below zero: M_3 performed best (CC: $\Delta\text{AIC}_{M_3} = -27.05$; PP: $\Delta\text{AIC}_{M_3} = -28.81$), followed by M_2 (CC: $\Delta\text{AIC}_{M_2} = -24.49$; PP: $\Delta\text{AIC}_{M_2} = -28.23$), and then M_1 (CC: $\Delta\text{AIC}_{M_1} = -4.56$; PP: $\Delta\text{AIC}_{M_1} = -6.86$). This indicates that incorporating both previous stimulus duration and decision information better explained current perceptual decisions. In position-inconsistent conditions, although ΔAIC values were below zero (PC: $\Delta\text{AIC}_{M_1} = -1.04$, $\Delta\text{AIC}_{M_2} = -1.61$, $\Delta\text{AIC}_{M_3} = -2.58$; CP: $\Delta\text{AIC}_{M_1} = -0.88$, $\Delta\text{AIC}_{M_2} = -0.90$, $\Delta\text{AIC}_{M_3} = -1.69$), their magnitudes were relatively small (approaching –2). This suggests that the importance of previous trial information for current perceptual decisions decreased in position-inconsistent conditions (Figure 5 [Figure 5: see original paper]A).

Experiment 2: Generalization of Serial Dependence Across Visual Hemifields

Experiment 1 found that both stimulus and decisional serial dependence effects could be generated in central and peripheral visual fields, but only stimulus serial dependence fully transferred between fields, whereas decisional serial dependence only partially transferred. This suggests that stimulus serial dependence may originate in higher-level visual processing areas, while decisional serial dependence may be constrained to some extent by early visual cortex processing. To further test this hypothesis, Experiment 2 investigated the generalization of serial dependence across visual hemispheres. Due to anatomical separation of the brain's left and right hemispheres, visual information transfer across hemispheres differs across visual cortical areas: early visual cortex (such as V1) primarily receives visual information from the contralateral visual field, whereas higher-level visual processing areas exhibit greater cross-hemifield receptive field characteristics (Amano et al., 2009; Harvey & Dumoulin, 2011). Therefore, investigating the generalization of serial dependence across visual hemispheres can further reveal its potential neural locus: if serial dependence in duration perception originates from early visual cortex processing, it should show hemifield specificity; otherwise, it should transfer across hemispheres.

3.1 Participants

Twenty-four university students who had not participated in Experiment 1 voluntarily completed Experiment 2. All were right-handed with normal or corrected-to-normal vision and remained naïve to the experimental purpose. One participant was excluded from formal data analysis due to poor performance (PSE outside the test duration range), leaving a final sample of 23 participants (17 females; mean age = 19.3 years, SD = 1.96 years). All participants provided written informed consent before the experiment and received monetary compensation afterward.

3.1.3 Design

A 2 (current stimulus position: left vs. right visual field) × 2 (position consistency: consistent vs. inconsistent) within-subjects design was used. The dependent variable was the proportion of trials in which participants judged the current test stimulus duration as longer than the reference stimulus.

Current stimulus position referred to the location of the test stimulus in the current trial relative to central fixation, divided into left and right visual fields. Position consistency referred to whether the positions of test stimuli in current and previous trials were the same: when both appeared in the left visual field or both appeared in the right visual field, this was the position-consistent condition; when the current test stimulus appeared in the left visual field (or right visual field) while the previous test stimulus appeared in the right visual field (or left visual field), this was the position-inconsistent condition.

3.1.4 Procedure

The experimental procedure was similar to Experiment 1, with the following differences: in both learning and test phases of Experiment 2, the visual fixation point was presented at screen center, while visual stimuli were presented 5° to the left or right of fixation (Figure 1B). Participants were required to maintain fixation on the central point throughout the experiment.

3.1.5 Data Analysis

As in Experiment 1, trials with reaction times exceeding three MADs from each participant's median RT were first excluded (Leys et al., 2013), removing 6.5%

of trials. We then computed each participant's |PSE–520| and JND for each condition to assess duration perception accuracy and sensitivity. To examine serial dependence across conditions, trials were divided into four groups: previous stimulus in left visual field and current stimulus in left visual field (LL); previous stimulus in right visual field and current stimulus in right visual field (RR); previous stimulus in right visual field and current stimulus in left visual field (RL); and previous stimulus in left visual field and current stimulus in right visual field (LR). Subsequent probabilistic choice model analyses and statistics followed Experiment 1.

3.2 Results

Figure 6 [Figure 6: see original paper]A shows psychometric functions for a representative participant in Experiment 2 across different position conditions. Paired-sample t-tests revealed no significant differences in duration perception accuracy (|PSE–520|) (64.01 ms vs. 56.81 ms, t(22) = 0.87, p = 0.396, 95% CI [–10.05, 24.45]) or sensitivity (JND) (115.64 ms vs. 117.54 ms, t(22) = –0.34, p = 0.735, 95% CI [–13.34, 9.55]) between left and right visual field conditions (Figures 6B and 6C). This indicates that duration perception did not differ between left and right visual fields.

One-sample t-tests on β_{prev_stim} coefficients showed that β_{prev_stim} was significantly less than zero in all four conditions (LL: t(22) = –2.48, p = 0.021, Cohen's d = –0.52, 95% CI [–0.65, –0.06]; RR: t(22) = –2.43, p = 0.024, Cohen's d = –0.51, 95% CI [–0.67, –0.05]; RL: t(22) = –3.17, p = 0.004, Cohen's d = –0.66, 95% CI [–0.84, –0.17]; LR: t(22) = –2.97, p = 0.007, Cohen's d = –0.62, 95% CI [–0.81, –0.14]). A 2 (current stimulus position: left vs. right visual field) × 2 (position consistency: consistent vs. inconsistent) repeated-measures ANOVA revealed no significant main effects of current stimulus position (F(1, 22) = 0.01, p = 0.941) or position consistency (F(1, 22) = 0.96, p = 0.339), and no significant interaction (F(1, 22) = 0.02, p = 0.878) (Figure 7 [Figure 7: see original paper]A). These results further demonstrate that stimulus serial dependence in duration perception can occur in peripheral visual fields and is not constrained by stimulus spatial position, transferring across left and right visual fields.

One-sample t-tests also showed that β_{prev_choice} was significantly greater than zero in all four conditions (LL: t(22) = 11.50, p < 0.001, Cohen's d = 2.40, 95% CI [0.92, 1.33]; RR: t(22) = 8.49, p < 0.001, Cohen's d = 1.77, 95% CI [0.79, 1.30]; RL: t(22) = 4.50, p < 0.001, Cohen's d = 0.94, 95% CI [0.28, 0.77]; LR: t(22) = 4.66, p < 0.001, Cohen's d = 0.97, 95% CI [0.30, 0.78]). A two-way repeated-measures ANOVA revealed a significant main effect of position consistency (F(1, 22) = 68.36, p < 0.001, $p^2 = 0.76$), with β_{prev_choice} significantly larger in position-consistent than inconsistent conditions. Neither the main effect of current stimulus position (F(1, 22) = 0.26, p = 0.616) nor the interaction (F(1, 22) = 0.60, p = 0.449) was significant (Figure 7B). These results indicate that decisional serial dependence in duration perception can only partially transfer across left and right visual fields, as spatial position consistency significantly modulated the effect.

Model comparison results in Experiment 2 showed that in position-consistent conditions, ΔAIC values were clearly below zero (LL: $\Delta\text{AIC}_{M_1} = –7.30$, $\Delta\text{AIC}_{M_2} = –25.74$, $\Delta\text{AIC}_{M_3} = –25.48$; RR: $\Delta\text{AIC}_{M_1} = –6.46$, $\Delta\text{AIC}_{M_2} = –23.83$, $\Delta\text{AIC}_{M_3} = –23.81$), indicating that models incorporating previous trial information (both stimulus duration and decision) performed better than the baseline model, confirming the influence of previous trial information on current decisions. In position-inconsistent conditions, model comparison also showed that models incorporating previous trial information (such as M_3) were better than the baseline model (M_0) (RL: $\Delta\text{AIC}_{M_1} = 0.06$, $\Delta\text{AIC}_{M_2} = –4.95$, $\Delta\text{AIC}_{M_3} = –5.67$; LR: $\Delta\text{AIC}_{M_1} = –1.51$, $\Delta\text{AIC}_{M_2} = –6.94$, $\Delta\text{AIC}_{M_3} = –7.09$). However, this advantage was relatively weaker compared to position-consistent conditions, again demonstrating that stimulus position consistency modulates serial dependence effects.

Experiment 1 suggested that stimulus serial dependence effects might be weaker in peripheral than central visual field. To further verify this, we averaged β_{prev_stim} across the four conditions in Experiment 2 and compared it with the average of the two central visual field conditions in Experiment 1 (CC and PC). Results showed that β_{prev_stim} was smaller (more negative) in central visual field conditions than in bilateral visual field conditions (–0.80 vs. –0.42, t(45) = –2.14, p = 0.038, Cohen's d = –0.63, 95% CI [–0.73, –0.02]), again demonstrating that stimulus serial dependence is attenuated when stimuli are presented in peripheral visual field.

Additionally, to reveal differences in decisional serial dependence generalization between non-homogeneous visual fields (Experiment 1: central vs. peripheral) and homogeneous visual fields (Experiment 2: left vs. right peripheral), we computed transfer magnitude by subtracting the mean β_{prev_choice} in position-inconsistent conditions (Experiment 1: PC and CP; Experiment 2: RL and LR) from the mean in position-consistent conditions (Experiment 1: CC and PP; Experiment 2: LL and RR). Larger differences indicate smaller transfer. Independent-samples t-tests showed that transfer magnitude was significantly smaller between non-homogeneous visual fields than between homogeneous visual fields (1.01 vs. 0.55, t(45) = 4.64, p < 0.001, Cohen's d = 1.35, 95% CI [0.26, 0.65]), indicating greater generalization of decisional serial dependence across homogeneous visual fields (left-right peripheral fields) than across non-homogeneous fields (central-peripheral).

Experiment 3: Generalization of Serial Dependence Across Different Spatial Reference Frames

In Experiments 1 and 2, participants always fixated on a single fixation point, meaning that when stimuli appeared at different screen locations, both their external and retinal spatial positions changed. Therefore, the above results cannot definitively determine whether the partial constraint of spatial information on decisional serial dependence arises from changes in external spatial position or retinal spatial position. Given that early visual cortex and higher-level visual areas (such as VIP) show sensitivity to different types of spatial information (retinotopic vs. spatiotopic) (Duhamel et al., 1997; Kastner et al., 2001), it is necessary to further investigate the spatial generalization of serial dependence in duration perception while dissociating these two spatial reference frames. Additionally, to examine whether the spatial generalization of stimulus and decisional serial dependence is affected by transfer distance, Experiment 3 used a transfer distance of 20° (greater than the 10° in Experiments 1 and 2) for both external and retinal spatial changes. Investigating these issues can further reveal the potential neural loci of serial dependence in duration perception.

4.1 Participants

Twenty-four university students (19 females; mean age = 19.8 years, SD = 2.41 years) who had not participated in Experiments 1 or 2 voluntarily completed Experiment 3. All were right-handed with normal or corrected-to-normal vision and remained naïve to the experimental purpose. Participants provided written informed consent before the experiment and received monetary compensation afterward.

4.1.2 Stimuli and Apparatus

The stimuli and apparatus in Experiment 3 were similar to Experiment 1, with the following differences: stimuli were presented on a high-refresh-rate LCD monitor (refresh rate = 120 Hz, resolution = 1920$×$1080 pixels). Additionally, because fixation position changed in this experiment, an Eyelink Portable Duo eye tracker (sampling rate = 500 Hz, right eye recording) was used to monitor participants' eye movements in real-time to ensure compliance with fixation shift instructions.

4.1.3 Design

A single-factor within-subjects design was employed, with the independent variable being the positional relationship between stimuli in previous and current trials, with four levels: spatiotopic change (SC), retinotopic change (RC), both spatiotopic and retinotopic change (both-change condition; BC), and neither change (no-change condition; NC). The dependent variable was the proportion of trials in which participants judged the current test stimulus duration as longer than the reference stimulus.

As shown in Figure 8 [Figure 8: see original paper], the spatiotopic change condition involved changes in external spatial position between previous and current trials while maintaining constant relative retinal position. The retinotopic change condition involved changes in relative retinal position while maintaining constant external spatial position. The both-change condition involved changes in both external spatial position and relative retinal position. The no-change condition involved no changes in either external spatial position or relative retinal position.

4.1.4 Procedure

Experiment 3 used the duration bisection task, similar to Experiment 1. As shown in Figure 8, three stimulus types were used: fixation left of center with stimulus above center (LUC); fixation right of center with stimulus above center (RUC); and fixation right of center with stimulus above-right of fixation (RUR).

The experiment consisted of five parts. To better monitor eye movements, a 5-point eye tracker calibration was performed before each part. The first part included both learning and test tasks, while parts 2–5 included only test tasks. In the learning task, the three types of reference stimuli (duration = 520 ms) were randomly presented 15 times (5 times each). Each trial began with a red fixation point appearing on the left or right side of screen center, which participants were required to maintain throughout the trial. Trials only initiated after participants maintained fixation for 250 ms (defined as gaze position within 2° of the fixation point), followed by a 500 ms blank interval and then the reference stimulus. Participants only needed to memorize the reference duration without responding. If they felt they had not yet memorized it, they could repeat the learning phase until confident, then proceed to the formal test phase. The formal test phase followed a similar trial structure, except that test stimulus duration was randomly selected from five logarithmically spaced durations between 300–900 ms, and participants judged test stimulus duration based on their memory of the reference (response method identical to Experiment 1). Each test part comprised 210 trials (5 durations × 3 stimulus types × 14 repetitions), for a total of 1050 test trials per participant.

4.1.5 Data Analysis

As in Experiment 1, trials with reaction times exceeding three MADs from each participant's median RT were first excluded (Leys et al., 2013), removing 8.0% of trials. We then computed each participant's |PSE–520| and JND for each condition to assess duration perception accuracy and sensitivity. Probabilistic choice model analyses and statistics for each condition followed Experiment 1.

4.2 Results

Figure 9 [Figure 9: see original paper]A shows psychometric functions for a representative participant in Experiment 3 across different stimulus type conditions. Paired-sample t-tests revealed that duration perception accuracy (|PSE–520|) was significantly higher for RUC than LUC stimulus type (73.31 ms vs. 93.82 ms, t(23) = 2.18, p = 0.040, 95% CI [1.03, 39.99]), and marginally significantly higher than RUR type (73.31 ms vs. 91.29 ms, t(23) = –1.89, p = 0.072, 95% CI [–37.69, 1.74]). Accuracy did not differ significantly between LUC and RUR types (93.82 ms vs. 91.29 ms, t(23) = 0.38, p = 0.705, 95% CI [–11.15, 16.22]) (Figure 9B). These results suggest that duration perception precision was higher in the upper-left visual field than upper-right, possibly reflecting left visual field (right hemisphere) advantages in duration processing (Zhang et al., 2006). Notably, this hemifield advantage was not observed in Experiment 2, likely because stimuli were closer to central vision (5°) in that experiment.

Duration perception sensitivity (JND) did not differ significantly across the three stimulus types (LUC vs. RUC: 131.43 ms vs. 124.77 ms, t(23) = 0.95, p = 0.350, 95% CI [–7.78, 21.09]; LUC vs. RUR: 131.43 ms vs. 130.13 ms, t(23) = 0.17, p = 0.869, 95% CI [–14.85, 17.46]; RUC vs. RUR: 124.77 ms vs. 130.13 ms, t(23) = –0.65, p = 0.521, 95% CI [–22.32, 11.62]) (Figure 9C). These results indicate that stimulus type did not affect duration perception sensitivity.

One-sample t-tests on β_{prev_stim} coefficients showed that β_{prev_stim} was significantly less than zero in all four conditions (SC: t(23) = –5.84, p < 0.001, Cohen's d = –1.19, 95% CI [–1.66, –0.79]; RC: t(23) = –6.38, p < 0.001, Cohen's d = –1.30, 95% CI [–1.34, –0.68]; BC: t(23) = –6.21, p < 0.001, Cohen's d = –1.27, 95% CI [–1.58, –0.79]; NC: t(23) = –5.24, p < 0.001, Cohen's d = –1.07, 95% CI [–1.56, –0.68]). A one-way repeated-measures ANOVA revealed no significant main effect of positional relationship (F(3, 69) = 0.25, p = 0.861) (Figure 10 [Figure 10: see original paper]A). These results again demonstrate that stimulus serial dependence in duration perception is not constrained by spatial information.

One-sample t-tests also revealed that β_{prev_choice} was significantly greater than zero in all four conditions (SC: t(23) = 6.60, p < 0.001, Cohen's d = 1.35, 95% CI [0.45, 0.85]; RC: t(23) = 5.76, p < 0.001, Cohen's d = 1.18, 95% CI [0.34, 0.72]; BC: t(23) = 7.18, p < 0.001, Cohen's d = 1.47, 95% CI [0.50, 0.90]; NC: t(23) = 9.90, p < 0.001, Cohen's d = 2.02, 95% CI [0.93, 1.43]). A one-way repeated-measures ANOVA revealed a significant main effect of position change (F(3, 69) = 8.54, p < 0.001). Post-hoc tests (Bonferroni) showed that β_{prev_choice} in the no-change condition (NC) was significantly larger than in change conditions (SC: pbonf < 0.001, Cohen's d = -1.30; RC: pbonf = 0.002, Cohen's d = -1.07; BC: pbonf = 0.006, Cohen's d = -0.96) (Figure 10B). This indicates that changes in either retinotopic or spatiotopic position led to partial reduction of decisional serial dependence.

In Experiment 3, the three stimulus types (LUC, RUC, RUR) were randomly presented, resulting in more trials for the no-change condition (NC) than for position-change conditions (SC, RC, BC). Since trial number can affect model estimation, we conducted a supplementary analysis. This analysis was similar to the main analysis, except that before model estimation, we first calculated the mean number of trials across the three position-change conditions for each participant, then randomly selected the same number of trials from the no-change condition. Results showed that even after equating trial numbers, decisional serial dependence in the no-change condition remained significantly larger than in position-change conditions (see Appendix, Figure S2).

Finally, model comparison results showed that in the no-change condition (NC), ΔAIC values were clearly below zero: M_3 performed best ($\Delta\text{AIC}_{M_3} = -21.35$), followed by M_2 ($\Delta\text{AIC}_{M_2} = -17.27$), and then M_1 ($\Delta\text{AIC}_{M_1} = -2.21$). This result, consistent with Experiments 1 and 2, indicates that incorporating previous trial information better explained participants' current decisions. However, in position-change conditions, ΔAIC values were relatively small (SC: $\Delta\text{AIC}_{M_1} = -0.07$, $\Delta\text{AIC}_{M_2} = 0.22$, $\Delta\text{AIC}_{M_3} = -1.64$; RC: $\Delta\text{AIC}_{M_1} = -0.09$, $\Delta\text{AIC}_{M_2} = 0.12$, $\Delta\text{AIC}_{M_3} = -1.38$; BC: $\Delta\text{AIC}_{M_1} = 0.44$, $\Delta\text{AIC}_{M_2} = -1.59$, $\Delta\text{AIC}_{M_3} = -3.09$). This suggests that the importance of previous trial information for current decisions was significantly reduced in position-inconsistent conditions (Figure 5C).

General Discussion

This study investigated stimulus and decisional serial dependence in visual duration perception and their spatial generalization through three experiments. The results demonstrate that both previous stimulus duration and previous decision responses exert important influences on current duration perception decisions. Specifically, previous stimulus duration produces a repulsive effect, shifting current duration perception away from previous stimulus duration (stimulus serial dependence), whereas previous decision responses produce an attractive effect, biasing current perceptual decisions toward previous choices (decisional serial dependence). Furthermore, we found that stimulus serial dependence is not constrained by external or retinal spatial positions. However, while decisional serial dependence can occur in both central and peripheral visual fields, it only partially transfers across different external and retinal spatial positions. These findings verify the independent influences of previous stimulus duration and previous decisions on subsequent duration perception in the visual modality and suggest distinct underlying mechanisms for these two effects.

Previous research using traditional psychophysical methods has investigated serial dependence in duration perception (Wehrman et al., 2020; Wiener et al., 2014). However, results showed both stimulus and decisional serial dependence effects in the auditory modality (Wiener et al., 2014) but only decisional serial dependence in the visual modality (Wehrman et al., 2020; Wiener et al., 2014). Because traditional psychophysical methods cannot completely separate these effects and their directions may be opposite, this pattern may have occurred because decisional serial dependence is stronger than stimulus serial dependence in vision, masking the latter. This study used a probabilistic choice model to dissociate the effects of previous stimulus duration and previous decisions on subsequent duration perception, revealing both effects with opposite directions in the visual modality. This finding aligns with a recent study, further demonstrating that both previous stimulus duration and previous decisions can significantly influence subsequent duration perception (Li et al., 2023).

We found that stimulus serial dependence in duration perception can transfer across different spatial positions, similar to duration aftereffects produced by long-term adaptation. Duration aftereffects also manifest as repulsive effects (negative aftereffects) that transfer across spatial positions (Li, Yuan, Chen, et al., 2015), suggesting similar underlying mechanisms. This supports the view that stimulus serial dependence in duration perception may be a short-term rapid adaptation phenomenon (Li et al., 2023). Notably, some studies have found that duration aftereffects are influenced by adaptation duration, with short-term adaptation (a single adaptation stimulus) failing to produce duration aftereffects (Heron et al., 2012; Li et al., 2017), which seems inconsistent with our findings. However, these previous studies did not account for the influence of previous trial decisions and used longer inter-trial intervals than our study, which may have weakened adaptation effects. In summary, our study provides further experimental evidence for rapid adaptation effects in duration perception.

Experiment 1 showed that compared to central visual field, both accuracy and sensitivity of duration perception were significantly reduced when stimuli were presented in peripheral visual field. Given that attentional resources are more available in central than peripheral vision (Shapiro & Johnson, 1987) and that attention is an important factor affecting duration perception (Matthews & Meck, 2016), one possible explanation is that reduced attention to peripheral stimuli leads to lower duration perception accuracy and sensitivity. Additionally, attention may affect duration perception by influencing visual processing quality. Previous research has shown that visual processing precision and acuity decrease gradually with eccentricity (Rosenholtz, 2016; Strasburger et al., 2011). Since duration perception is closely related to stimulus representation clarity (Matthews & Meck, 2016), this can also explain why duration perception accuracy and sensitivity were reduced for peripheral compared to central stimuli. Nevertheless, we found significant stimulus serial dependence effects in both central and peripheral visual fields, consistent with previous orientation perception research (Fischer & Whitney, 2014; Pascucci et al., 2019). Moreover, stimulus serial dependence (but not decisional dependence) was attenuated for peripheral compared to central stimuli, indicating that stimulus serial dependence also depends on attention or stimulus representation clarity.

In the visual processing pathway, receptive fields of different neurons increase with neural hierarchy and stimulus eccentricity (Smith et al., 2001). For example, human fMRI studies have found that population receptive fields in early visual cortex (V1–V4) do not exceed 7° even at large eccentricities (e.g., 8°) and are largely restricted to the contralateral visual field, whereas later visual cortex (such as MT/MST) has larger population receptive fields and greater cross-hemifield generalization (Amano et al., 2009; Harvey & Dumoulin, 2011). This characteristic of visual cortex is also supported by electrophysiological studies in animals (e.g., monkeys) (Gattass et al., 1988). In our study, the distance between central and peripheral stimuli (Experiment 1) and between left and right hemifield stimuli (Experiment 2) was 10°. Results showed that stimulus serial dependence not only fully transferred between central and peripheral visual fields but also across left and right hemifields. The effect's generalization was not modulated by spatial type (external vs. retinal space) and did not decrease with increasing transfer distance (in Experiment 3, both external and retinal transfer distances were 20°, yet full generalization was still observed). This pattern first excludes the hypothesis that stimulus serial dependence in duration perception originates in early visual cortex. Given that stimulus serial dependence is essentially a sensory adaptation aftereffect, these results suggest that the influence of previous stimulus duration on subsequent duration perception likely occurs in higher-level visual processing areas that are insensitive to spatial information or have large receptive fields (at least >20°). Recent fMRI research has found duration-selective neurons in the human right parietal lobe, and neural adaptation in this region can predict the magnitude of visual duration aftereffects (Hayashi & Ivry, 2020). Combined with this finding, we speculate that this brain region may also be the potential neural locus of stimulus serial dependence in duration perception. Therefore, our results do not support the view that long-term and rapid adaptation mechanisms in visual duration perception originate from neural adaptation in different brain regions.

Unlike stimulus serial dependence, we found that decisional serial dependence in duration perception only partially transfers across different spatial positions, with spatial information exerting partial constraints on this effect. However, this constraint is not modulated by spatial type. These results do not fully support the hypothesis that decisional serial dependence originates in early visual cortex. The simultaneous constraints from both external and retinal space seem to reflect involvement of both early and higher-level visual cortex in decisional serial dependence, or alternatively, the involvement of a brain region sensitive to both external and retinal spatial position changes during visual duration representation. However, these hypotheses cannot easily explain the cross-experiment comparison results showing smaller transfer magnitude between non-homogeneous visual fields (central-peripheral) than between homogeneous visual fields (left-right peripheral).

Another possible explanation is that the constraining effect of spatial information on decisional serial dependence originates from categorical organization mechanisms in higher cognitive brain regions (Li et al., 2023). Indeed, previous research has found that decisional serial dependence is influenced by stimulus categories and similarity between successive stimuli (Feigin & Baror et al., 2021; Petzold & Haubensak, 2004). For example, Petzold and Haubensak (2004) found that when participants were instructed to treat different colored stimuli as different categories, size perception serial dependence was constrained by stimulus color; conversely, when instructed to treat them as the same category, the effect transferred across colors. According to this hypothesis, when spatial positions of stimuli are consistent across previous and current trials, they are more easily categorized together, making perceptual decisions based on these stimuli more correlated. Conversely, stimuli at different spatial positions are less easily categorized together, reducing the correlation between perceptual decisions. Therefore, previous decisions have less influence on subsequent decisions under spatially inconsistent conditions, resulting in weaker decisional serial dependence. This high-level categorical organization mechanism involves advanced cognitive processing (such as memory or decision-making) and is quite flexible, operating based on either retinotopic or spatiotopic position. As long as participants are aware of spatial position changes between trials, this categorical organization mechanism is engaged, and the degree of reduction in decisional serial dependence under spatially inconsistent conditions depends primarily on the categorical difference between successive trials. This can partially explain why decisional serial dependence transfer is smaller between non-homogeneous than homogeneous visual fields. Nagai et al. (2012) found that spatial position cues facilitate the influence of different stimulus distributions on temporal order perception, suggesting that spatial position-based categorical organization is crucial for forming prior information about multiple categories. This further supports the categorical organization hypothesis. Under this explanatory framework, decisional serial dependence in duration perception may originate in brain regions related to memory or decision-making, such as posterior parietal cortex (PPC) and prefrontal cortex (PFC). Previous research has found that these regions retain information about previous decisions and play important roles in decisional serial dependence (Hwang et al., 2017; Mochol et al., 2021). However, it should be noted that this behavioral study can only infer potential neural mechanisms based on behavioral patterns; related hypotheses require further testing using cognitive neuroscience techniques (such as fMRI and TMS).

Combined with the above analysis, the attractive decisional serial dependence in duration perception found in this study may be consistent with decision inertia phenomena (the tendency to repeat previous decisions) found in other perceptual domains (Akaishi et al., 2014; Pascucci et al., 2019). This phenomenon reflects an "automatic learning mechanism" through which individuals continuously update the likelihood of current perceptual decisions based on previous choices (Akaishi et al., 2014). Our study found that in duration perception, this decisional serial dependence is partially constrained by spatial position consistency between previous and current trials: although significant decisional serial dependence was observed in both consistent and inconsistent conditions, the effect was significantly larger in consistent conditions. This suggests that this automatic decision sequence learning mechanism depends to some extent on the spatial context of stimulus sequences.

Conclusion

Using a duration bisection task and probabilistic choice model, this study investigated the effects of previous stimulus duration and previous decision responses on subsequent duration perception. The results showed that: (1) previous stimulus duration produced a significant stimulus serial dependence effect (repulsive effect) that fully transferred across different spatial positions; (2) previous decision responses produced a significant decisional serial dependence effect (attractive effect) that was modulated by spatial position consistency between previous and current trials and only partially transferred across different spatial positions; and (3) the spatial generalization of both stimulus and decisional serial dependence effects was not modulated by spatial type. These findings confirm that previous stimuli and previous decisions exert different influences (repulsive vs. attractive) on subsequent duration perception in visual duration perception. Furthermore, investigating spatial generalization reveals distinct mechanisms: stimulus serial dependence, unconstrained by spatial information and similar to duration aftereffects, may originate in higher-level visual processing areas insensitive to spatial information or with large receptive fields; decisional serial dependence, partially constrained by spatial information, may primarily originate in higher cognitive brain areas with categorical organization functions. This study enhances understanding of the plasticity and underlying mechanisms of duration perception.

References

Akaishi, R., Umeda, K., Nagase, A., & Sakai, K. (2014). Autonomous mechanism of internal choice estimate underlies decision inertia. *Neuron, 81*(1), 195–206.

Amano, K., Wandell, B. A., & Dumoulin, S. O. (2009). Visual field maps, population receptive field sizes, and visual field coverage in the human MT+ complex. *Journal of Neurophysiology, 102*(5), 2704–2718.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Brimijoin, W. O., & O'Neill, W. E. (2010). Patterned tone sequences reveal nonlinear interactions in auditory spectrotemporal receptive fields in the inferior colliculus. *Hearing Research, 267*(1–2), 96–110.

Burr, D., Tozzi, A., & Morrone, M. C. (2007). Neural mechanisms for timing visual events are spatially selective in real-world coordinates. *Nature Neuroscience, 10*(4), 423–425.

Cicchini, G. M., Benedetto, A., & Burr, D. C. (2021). Perceptual history propagates down to early levels of sensory analysis. *Current Biology, 31*(6), 1245–1250.

Duhamel, J.-R., Bremmer, F., Ben Hamed, S., & Graf, W. (1997). Spatial invariance of visual receptive fields in parietal cortex neurons. *Nature, 389*(6653), 845–848.

Fang, F., Murray, S. O., Kersten, D., & He, S. (2005). Orientation-tuned fMRI adaptation in human visual cortex. *Journal of Neurophysiology, 94*(6), 4188–4195.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*(2), 175–191.

Feigin, H., Baror, S., Bar, M., & Zaidel, A. (2021). Perceptual decisions are biased toward relevant prior choices. *Scientific Reports, 11*, 648.

Feigin, H., Shalom-Sperber, S., Zachor, D. A., & Zaidel, A. (2021). Increased influence of prior choices on perceptual decisions in autism. *Elife, 10*, e61595.

Fischer, C., Czoschke, S., Peters, B., Rahm, B., & Bledowski, C. (2020). Context information supports serial dependence of multiple visual objects across memory episodes. *Nature Communications, 11*(1), 1–11.

Fischer, J., & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience, 17*(5), 738–743.

Gattass, R., Sousa, A. P., & Gross, C. G. (1988). Visuotopic organization and extent of V3 and V4 of the macaque. *Journal of Neuroscience, 8*(6), 1831–1845.

Harvey, B. M., & Dumoulin, S. O. (2011). The relationship between cortical magnification factor and population receptive field size in human visual cortex: Constancies in cortical architecture. *Journal of Neuroscience, 31*(38), 13604–13612.

Hayashi, M. J., & Ivry, R. B. (2020). Duration selectivity in right parietal cortex reflects the subjective experience of time. *Journal of Neuroscience, 40*(40), 7749–7758.

Heron, J., Aaen-Stockdale, C., Hotchkiss, J., Roach, N. W., McGraw, P. V., & Whitaker, D. (2012). Duration channels mediate human time perception. *Proceedings of the Royal Society B: Biological Sciences, 279*(1729), 690–698.

Huang, X. T., Guo, X. Y., & Nie J. (2003). The relationship between temporal and non-temporal information in cognitive processing. *Psychological Science, 26*(5), 770–774. [黄希庭, 郭秀艳, 聂晶. (2003). 认知加工中时间与非时间信息的相互关系. 心理科学, 26(5), 770–774.]

Hwang, E. J., Dahlen, J. E., Mukundan, M., & Komiyama, T. (2017). History-based action selection bias in posterior parietal cortex. *Nature Communications, 8*(1), 1242.

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the American Statistical Association, 90*(430), 773–795.

Kastner, S., De Weerd, P., Pinsk, M. A., Elizondo, M. I., Desimone, R., & Ungerleider, L. G. (2001). Modulation of sensory suppression: Implications for receptive field sizes in the human visual cortex. *Journal of Neurophysiology, 86*(3), 1398–1411.

Knapen, T., Rolfs, M., Wexler, M., & Cavanagh, P. (2010). The reference frame of the tilt aftereffect. *Journal of Vision, 10*(1), 1–13.

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *Journal of Experimental Social Psychology, 49*(4), 764–766.

Li, B., Wang, B., & Zaide, A. (2023). Modality-specific sensory and decisional carryover effects in duration perception. *BMC Biology, 21*: 48.

Li, B., Xiao, L., Yin, H., Liu, P., & Huang, X. (2017). Duration aftereffect depends on the duration of adaptation. *Frontiers in Psychology, 8*, 491.

Li, B., Yuan, X., Chen, Y., Liu, P., & Huang, X. (2015). Visual duration aftereffect is position invariant. *Frontiers in Psychology, 6*, 1536.

Li, B., Yuan, X., & Huang, X. (2015). The aftereffect of perceived duration is contingent on auditory frequency but not visual orientation. *Scientific Reports, 5*, 10124.

Liberman, A., Fischer, J., & Whitney, D. (2014). Serial dependence in the perception of faces. *Current Biology, 24*(21), 2569–2574.

Manassi, M., Kristjansson, A., & Whitney, D. (2019). Serial dependence in a simulated clinical visual search task. *Scientific Reports, 9*(1), 19937.

Matthews, W. J., & Meck, W. H. (2016). Temporal cognition: Connecting subjective time to perception, attention, and memory. *Psychological Bulletin, 142*(8), 856–907.

Merchant, H., Harrington, D. L., & Meck, W. H. (2013). Neural basis of the perception and estimation of time. *Annual Review of Neuroscience, 36*, 313–336.

Michele, F., & Joonkoo, P. (2018). Serial dependence in numerosity perception. *Journal of Vision, 18*(9): 15, 1–12.

Mochol, G., Kiani, R., & Moreno-Bote, R. (2021). Prefrontal cortex represents heuristics that shape choice bias and its integration into future behavior. *Current Biology, 31*(6), 1234–1244.e6.

Moon, J., & Kwon, O. S. (2022). Attractive and repulsive effects of sensory history concurrently shape visual perception. *BMC Biology, 20*(1), 247.

Nagai, Y., Suzuki, M., Miyazaki, M., & Kitazawa, S. (2012). Acquisition of multiple prior distributions in tactile temporal order judgment. *Frontiers in Psychology, 3*, 276.

Pascucci, D., Mancuso, G., Santandrea, E., Della Libera, C., Plomp, G., & Chelazzi, L. (2019). Laws of concatenated perception: Vision goes for novelty, decisions for perseverance. *Plos Biology, 17*, e3000144.

Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442.

Petzold, P., & Haubensak, G. (2004). The influence of category membership of stimuli on sequential effects in magnitude judgment. *Perception & Psychophysics, 66*(4), 665–678.

Qiu, A., Rosenau, B. J., Greenberg, A. S., Hurdal, M. K., Barta, P., Yantis, S., & Miller, M. I. (2006). Estimating linear cortical magnification in human primary visual cortex via dynamic programming. *Neuroimage, 31*(1), 125-138.

Rosenholtz, R. (2016). Capabilities and limitations of peripheral vision. *Annual Review of Neuroscience, 2*, 1–23.

Schutt, H. H., Harmeling, S., Macke, J. H., & Wichmann, F. A. (2016). Painfree and accurate bayesian estimation of psychometric functions for (potentially) overdispersed data. *Vision Research, 122*, 105–123.

Shapiro, K. L., & Johnson, T. L. (1987). Effects of arousal on attention to central and peripheral visual-stimuli. *Acta Psychologica, 66*(2), 157–172.

Shuler M. G. (2016). Timing in the visual cortex and its investigation. *Current Opinion in Behavioral Sciences, 8*, 1–6.

Smith, A. T., Singh, K. D., Williams, A., & Greenlee, M. (2001). Estimating receptive field size from fMRI data in human striate and extrastriate visual cortex. *Cerebral Cortex, 11*(12), 1182–1190.

St John-Saaltink, E., Kok, P., Lau, H. C., & de Lange, F. P. (2016). Serial dependence in perceptual decisions is reflected in activity patterns in primary visual cortex. *Journal of Neuroscience, 36*(23), 6186-6192.

Strasburger, H., Rentschler, I., & Juttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of Vision, 11*(5), 13.

Wandell, B. A., Dumoulin, S. O., & Brewer, A. A. (2007). Visual field maps in human cortex. *Neuron, 56*(2), 366–383.

Wehrman, J. J., Wearden, J., Sowman, P., & Psychophysics. (2020). Decisional carryover effects in interval timing: Evidence of a generalized response bias. *Attention, Perception, & Psychophysics, 82*(4), 2147–2164.

Wiener, M., Thompson, J. C., & Coslett, H. B. (2014). Continuous carryover of temporal context dissociates response bias from perceptual influence for duration. *Plos One, 9*(6), e100803.

Zhang, Z. J., Yuan, H., & Huang, X. T. (2006). The difference between sub-and supara-second interval processing: Evidence from an ERP study. *Psychological Science, 29*(1), 87–90. [张志杰, 袁宏, 黄希庭. (2006). 不同时距加工机制的比较: 来自 ERP 的证据 ( ). 心理科学, 29(1), 87–90.]

Appendix

Figure S1. Baseline bias (β_0) and current stimulus duration ($\beta_{current\_stim}$) coefficients across different position conditions (A, B show Experiment 1 results; C, D show Experiment 2 results; E, F show Experiment 3 results). CC = previous trial in central visual field, current trial in central visual field; PP = previous trial in peripheral visual field, current trial in peripheral visual field; PC = previous trial in peripheral visual field, current trial in central visual field; CP = previous trial in central visual field, current trial in peripheral visual field; LL =

previous trial in left visual field, current trial in left visual field; RR = previous trial in right visual field, current trial in right visual field; RL = previous trial in right visual field, current trial in left visual field; LR = previous trial in left visual field, current trial in right visual field; SC = spatiotopic change (fixation and stimulus positions both change but relative position remains constant); RC = retinotopic change (fixation changes but stimulus position remains constant); BC = both spatiotopic and retinotopic change; NC = no change (fixation and stimulus positions remain constant). Gray triangles represent individual participant data points; error bars represent standard errors; ***$p < 0.001$.

Figure S2. Previous stimulus duration (β_{prev_stim}) and decision response (β_{prev_choice}) coefficients across different position conditions in Experiment 3 (randomized results). SC = spatiotopic change; RC = retinotopic change; BC = both changes; NC = no change. Gray triangles represent individual participant data points; error bars represent standard errors; **$p < 0.001$, $p < 0.05$.

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

Source: ChinaXiv — Machine translation. Verify with original.