The Effect of Task Relevance on Numerosity Serial Dependence

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Date: 2023-11-20T00:00:00+00:00

Abstract

Sequential dependency effects reflect that current perceptual experience depends not only on immediate stimulus input but also on recent history. This effect is crucial for forming relatively stable perception in dynamically changing environments. This study used dot arrays as stimulus materials and employed an orthogonal design across two dimensions—numerosity/area (Experiment 1) or numerosity/size (Experiment 2)—to explore how task relevance affects sequential dependency effects of linear distribution features through an estimation task. Results showed that regardless of whether a feature was task-relevant, the same feature from the previous trial always exerted an opposite influence on perception in the current trial. For task-relevant features, sequential dependencies from the previous trial were consistently repulsive effects. For task-irrelevant features, if the irrelevant feature in the current trial positively predicted participants' perceptual responses, then the irrelevant feature from the previous trial produced a repulsive sequential dependency effect; conversely, if the irrelevant feature in the current trial negatively predicted participants' perceptual responses, then the irrelevant feature from the previous trial produced an attractive sequential dependency effect. The influence of task relevance on sequential dependency effects was primarily manifested in a reduction of effect magnitude. These findings reveal that sequential dependency effects of linear distribution features are jointly influenced by task relevance and the characteristics of the features themselves, while sequential dependency effects of irrelevant features suggest that sequential dependency effects can also occur at the object level.

Full Text

Preamble

The Effect of Task Relevance on Serial Dependence in Numerosity Perception

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Abstract

Serial dependence reflects that current perceptual experience is shaped not only by immediate sensory input but also by recent perceptual history. This effect is crucial for establishing relatively stable perceptions in dynamically changing environments. Using dot arrays as stimuli, the present study orthogonally manipulated numerosity/area (Experiment 1) or numerosity/size (Experiment 2) to investigate how task relevance influences serial dependence effects for linearly distributed features through estimation tasks. The results revealed that regardless of task relevance, the same feature from the previous trial consistently exerted an opposite influence on current trial perception compared to its effect in the current trial. For task-relevant features, serial dependence from the previous trial was always repulsive. For task-irrelevant features, however, the direction of serial dependence depended on the predictive relationship between the irrelevant feature and the observer's response in the current trial: when the irrelevant feature positively predicted the response, it produced repulsive serial dependence; when it negatively predicted the response, it yielded attractive serial dependence. Task relevance primarily modulated serial dependence by reducing its magnitude. These findings demonstrate that serial dependence for linearly distributed features is jointly influenced by task relevance and intrinsic feature characteristics, while the persistence of serial dependence in irrelevant features suggests that such effects can also emerge at the object level.

Keywords: serial dependence, numerosity perception, task relevance, linear distributed features

1. Introduction

Our sensory systems continuously receive vast amounts of stimulus information from the environment, which is often complex, variable, and noisy. When this information is processed in the brain, internal neural responses may also be accompanied by noise. Nevertheless, the world we perceive appears remarkably stable. How does the brain maintain continuous and stable perceptions in a rapidly changing environment? Recent research suggests that the brain may achieve this through an active filtering mechanism that attenuates both exogenous and endogenous noise, a process known as serial dependence (Fischer & Whitney, 2014).

Serial dependence refers to the phenomenon where perception of a current visual stimulus is influenced not only by the stimulus itself but also by past perceptual experiences, potentially causing systematic biases in current perception. While these biases are generally considered attractive—making the current stimulus appear more similar to the previous one—some studies have found repulsive biases that make the current stimulus appear more distinct from its predecessor (Cicchini et al., 2017; Fischer & Whitney, 2014; Pascucci & Plomp, 2021; Sun et al., 2020; Xu et al., 2022). Serial dependence may occur at various levels of information processing and representation (Cicchini et al., 2021; Fritsche et al., 2017; Xu et al., 2022). According to current paradigms and multiple studies, serial dependence is a multifactorial phenomenon, wherein prior perception, memory, decision-making, and specific task demands collectively influence decisions about current stimulus features (Fritsche et al., 2017; Fritsche & de Lange, 2019; Pascucci et al., 2019). Under this processing mechanism, our perceptual system may retain information from recent inputs, systematically biasing current perceptual content toward recent stimulus inputs, thereby reducing redundant information processing and neural noise. This internal mechanism is considered an explanation for perceptual stability: both past experience and current sensory input jointly determine our current perception.

Serial dependence effects have been widely observed across various visual tasks and stimuli, such as orientation perception (which follows a circular distribution in representational space) (Fischer & Whitney, 2014; Fritsche et al., 2017), color estimation (Barbosa & Compte, 2020), circular spatial position judgments (Manassi et al., 2018), and shape perception (Collins, 2022b). Additionally, serial dependence exists for features with linear distributions in representational space, such as numerosity (Cicchini et al., 2014; Fornaciai & Park, 2018b), time perception (Togoli et al., 2021), facial attractiveness perception (Van der Burg et al., 2019), and even statistical properties of stimulus ensembles like variability (Suárez-Pinilla et al., 2018). Linearly distributed features—such as number, area, distance, and luminance—vary unidirectionally within a certain range, whereas circularly distributed features—such as orientation, color, month, and angle—cycle back to their starting value after reaching the upper limit. Researchers have argued that due to their periodic nature, circularly distributed data are fundamentally different from linearly distributed data (Cremers & Klugkist, 2018). Given that sample spaces exhibit different distribution types, circular and linear data typically require different mathematical models for description and different statistical analysis methods (Cremers, 2021; Fisher, 1995; Fisher & Lee, 1992; Lagona, 2016; Ravindran & Ghosh, 2011).

According to previous research, the direction and strength of serial dependence for circular versus linear features are differentially affected by the physical difference in features between adjacent trials. In studies examining serial dependence for "circular" features such as orientation, when the orientation difference between two sequentially presented stimuli is small, observers' responses systematically bias toward the previous trial's orientation, demonstrating an attractive effect; when the orientation difference is large, however, the effect disappears or becomes repulsive, shifting perception away from the previous orientation (Fischer & Whitney, 2014; Fritsche et al., 2017). This phenomenon is typically modeled using the first derivative of a Gaussian function or a sine function. Other features conforming to circular distributions (i.e., von Mises distributions) exhibit serial dependence patterns similar to those observed in orientation judgments. However, serial dependence effects for linearly distributed visual features manifest differently. For instance, in numerosity studies, larger numbers of dots in the previous trial lead to greater overestimation of the current dot array, while smaller numbers in the previous trial lead to greater underestimation, demonstrating a monotonic influence of prior numerosity on current numerosity estimation (Cicchini et al., 2014; Fornaciai & Park, 2020). These differences between feature types may stem from distinct representational and processing mechanisms.

Although linearly distributed features are equally common in daily life, they have received less research attention compared to circular features. The present study investigates serial dependence for linear features using numerosity and related attributes as research objects. Numerosity perception is a fundamental numerical ability present across species (Cantlon et al., 2009; Kutter, 2018; Yang et al., 2017), involving rapid comprehension, evaluation, and processing of numerical information, as well as representing and understanding relationships between quantities (Dehaene, 2002). Numerosity has significant survival implications for many organisms—for example, fish choose larger shoals to reduce predation risk, and bees can identify flowers by petal count (Agrillo et al., 2016; Gross et al., 2009; Pisa & Agrillo, 2009). Moreover, numerosity is a foundational cognitive ability in humans and may even form the cognitive basis for advanced mathematical skills (Starr et al., 2013; Sadler & Tai, 2007). Therefore, investigating the processing mechanisms of numerosity is particularly important.

Multiple studies have demonstrated that the strength and direction of serial dependence are influenced by attention and task relevance (Fischer et al., 2020; Fornaciai & Park, 2019a; Fritsche & de Lange, 2019). Some research has found that serial dependence occurs even during passive viewing without an explicit task (Fornaciai & Park, 2018a), indicating that task-irrelevant stimuli can also produce serial dependence. Pascucci et al. (2019) found that when participants were explicitly instructed that certain trials did not require orientation reproduction reports, the attractive effect disappeared and even became repulsive for subsequent orientation perception. Consistent with this, substantial evidence supports the critical role of attention in serial dependence: task-relevant locations or features receive more attention and produce stronger attractive effects. For example, when multiple stimuli are presented simultaneously, observers' perception of a target grating's orientation biases toward the orientation of the grating at the target location in the previous trial, demonstrating attractive serial dependence at attended locations; however, for previously unattended (task-irrelevant) locations, the attractive effect weakens or even becomes repulsive (Fischer & Whitney, 2014; Fornaciai & Park, 2018b). Beyond spatial attention, serial dependence is also modulated by feature attention. Even for different features of the same object (e.g., size and orientation, color and motion direction), when attention is directed to one feature, serial dependence on the other feature is substantially reduced (Fischer et al., 2020; Fritsche & de Lange, 2019).

Although most of this evidence supports the influence of task relevance on serial dependence, these studies have primarily focused on circularly distributed features such as orientation or position. As previously noted, serial dependence for linear spatial features differs from that for circular features, and the underlying mechanisms may also differ. Numerosity perception is not only a fundamental visual feature but also a representative linear spatial feature (Anobile et al., 2012; DeWind et al., 2015; Kutter et al., 2022). When dot arrays differ in numerosity, other stimulus properties such as individual dot size (Item Area, IA), dot density, and field area (Field Area, FA) may also differ. These attributes interact and jointly determine what we perceive (Franconeri et al., 2009; Harvey et al., 2015; Tokita & Ishiguchi, 2010). Given that different attributes of dot arrays may interfere with each other during perception, does this interference enter the stimulus history and manifest in serial dependence effects? What are the characteristics of serial dependence for different stimulus attributes when they serve as task-irrelevant versus task-relevant features?

To date, only a few studies have examined how task relevance influences serial dependence among numerosity and related features. For example, research based on numerosity and time perception found that when these features served as irrelevant dimensions, neither produced attractive effects on the other (Togoli et al., 2021). Additionally, numerosity and the average area of individual dots in an array only influenced their own serial dependence when they were task-relevant features (Fornaciai et al., 2023). Using event-related potentials (ERP), one study found that although neither numerosity nor size showed cross-feature serial dependence behaviorally, their representations could be decoded from neural signals when they were task-irrelevant features (Fornaciai et al., 2023).

Although these numerosity studies have attempted to explore how task relevance affects serial dependence for linear features, they employed paradigms that differ from classic serial dependence research. Studies investigating serial dependence for circular features commonly use reproduction/estimation tasks (adjustment tasks) (Cicchini et al., 2018; Fischer & Whitney, 2014), such as the classic orientation reproduction paradigm. In contrast, studies on serial dependence for "linearly represented" features like numerosity typically use forced-choice tasks (Cicchini et al., 2021; Fornaciai & Park, 2018b, 2019b, 2020). Reproduction/estimation tasks require participants to adjust a response tool to match their perceived stimulus feature as accurately as possible. Forced-choice tasks typically require participants to compare a specific feature (e.g., orientation, numerosity) between a target and a reference stimulus (Cicchini et al., 2021; Fritsche et al., 2017), revealing whether an inducer stimulus alters perception of the target stimulus through shifts in psychometric functions.

Reproduction/estimation and forced-choice tasks differ in several key aspects. First, forced-choice tasks primarily focus on how an inducer stimulus within the same trial influences perception of a probe stimulus (Fornaciai & Park, 2018b, 2019b; Togoli et al., 2021). In this paradigm, participants are not required to report their perception of the inducer stimulus itself, so perceptual processing of task-irrelevant features is not explicitly suppressed, and the accuracy or extent of inducer processing cannot be determined. In reproduction/estimation paradigms, however, participants must report the task-relevant feature for stimuli in both the previous and current trials, minimizing perceptual processing of irrelevant features. Second, forced-choice tasks impose fewer cognitive demands, as participants do not necessarily need to complete a non-symbolic to symbolic conversion. Reproduction/estimation tasks involve more advanced perceptual stages such as memory. Finally, in classic reproduction/estimation paradigms, the features of stimuli in previous trials typically have multiple levels, whereas in previous forced-choice tasks, inducer stimuli have had fewer feature levels, potentially limiting experimental validity. In summary, to directly compare serial dependence between linear and circular features while excluding potential confounds from experimental paradigms, we chose to use reproduction/estimation tasks to investigate serial dependence in numerosity perception.

The present study aims to apply the classic serial dependence paradigm and, through both numerosity and area estimation tasks, investigate how task relevance influences serial dependence for linear features and its underlying mechanisms. In studies of numerosity serial dependence, participants are typically presented with a series of dot arrays and asked to estimate the number of dots or identify which array contains more dots (Castaldi et al., 2018; Cicchini et al., 2014; Fornaciai & Park, 2018b, 2020). The current study also uses dot arrays as stimuli, with numerosity and dot array area (Experiment 1) or numerosity and dot size (Experiment 2) varied orthogonally. Previous research has found that both the physical features of prior stimuli and participants' responses influence current judgments, and when examined together in the same model rather than separately, the resulting serial dependence effects differ substantially (Shan & Postle, 2022; Stern et al., 2022). In the present study, we treat the physical features of stimuli and participants' responses as independent variables and establish Generalized Linear Mixed-effects Models (GLMM). As a powerful statistical tool, GLMM can handle different response variable distributions, making the model more flexible. It can simultaneously consider both fixed and random effects, thereby better accounting for individual differences between participants and complex interaction effects in experimental designs, thus providing more precise and robust estimates (Bolker et al., 2009). We will determine the optimal model through model comparison and further analyze the contributions of physical stimulus features and participant responses to serial dependence in this model.

2.1 Experiment 1 Purpose

This experiment used an estimation task to evaluate the behavioral characteristics of serial dependence in numerosity and area estimation, as well as the influence of numerosity and area as task-irrelevant features on subsequent perception of area or numerosity. We hypothesized that task relevance would affect serial dependence in the estimation task. In the numerosity estimation task, since numerosity is task-relevant, its serial dependence effect should be stronger, while area as a task-irrelevant feature should show weaker serial dependence. The opposite pattern was expected in the area estimation task.

2.2.1 Participants

Using G*Power 3.1.9 software (Faul et al., 2009) with an effect size f^2 of 0.3, power ($1-\beta$) of 80%, and α level of 0.05, the required sample size was calculated to be 29 participants. Experiment 1 actually recruited 33 participants, including 25 females with a mean age of 21.15 years. All were students at Beijing Normal University with normal or corrected-to-normal vision, no color blindness or weakness, and right-handed. None were mathematics majors or psychology majors above the sophomore level. The study was approved by the Experimental Ethics Committee of the Faculty of Psychology at Beijing Normal University, and participants received monetary compensation.

2.2.2 Apparatus and Materials

The experiment was conducted in a quiet, dark room using a 27-inch flat-screen color monitor with a vertical refresh rate of 59 Hz and resolution of 2560$×1440.Thescreenbackgroundwasgraywithaluminanceof10cd/m^{2}.Participantsviewedthescreenfromadistanc
During the experiment, different dot arrays were presented as images, with 20 different dot array images generated for each level, totaling 980 images. On each trial, a target stimulus was randomly selected without replacement from the corresponding level's image pool. Experimental procedures and response recording were controlled by MATLAB (Matlab R2018b, The Mathworks, Inc., Natick, Massachusetts, USA) and the Psychtoolbox-3 extension (Brainard, 1997).

2.2.3 Experimental Design

The experiment employed a 7$×7×2blockdesign,witheachparticipantcompletingallexperimentalconditions.T
(1)numerosity,rangingfrom8to32dotswithsevenlevels;(2)arrayarea,rangingfrom40.1to160.3degree^{2}$
with seven levels; and (3) task relevance: in the numerosity estimation task, participants attended to numerosity (task-relevant) while area was task-irrelevant, whereas in the area estimation task, participants attended to array area (task-relevant) while numerosity was task-irrelevant. The order of the two tasks was counterbalanced across participants. Participants' estimates of the task-relevant feature were recorded.

2.2.4 Procedure

Using the numerosity estimation task as an example, the experimental procedure is illustrated in Figure 1 [Figure 1: see original paper]. First, a black fixation cross appeared at the center of the screen for 1350–1450 ms, requiring participants to maintain fixation. Next, a stimulus image was presented: a dot array appeared at the center of the screen for 250 ms. Then, the task instruction "Please estimate the number of dots as accurately as possible" was presented at the top of the screen, with a number axis below. The axis endpoints were labeled "5" and "40." After participants clicked on the axis with the mouse, a white tick mark appeared at the clicked location, displaying the corresponding value below it. Participants were informed before the experiment that there was no time limit during the response phase and that they should estimate as accurately as possible. Multiple clicks were permitted until participants pressed the Enter key to confirm, at which point the scale value was recorded as their estimate. Participants had 15 seconds to respond; if they failed to press Enter within this time, the program automatically advanced to the next trial and the response was recorded as "N/A." The instruction and number axis were positioned above the stimulus image, non-overlapping with the dot array presentation location.

The experiment consisted of two parts: numerosity estimation and area estimation. In each task condition, all experimental levels were presented randomly. The entire experiment comprised 588 trials divided into six blocks, with each task containing three consecutive blocks of 98 trials each. Task order was counterbalanced across participants. Practice was required before each experimental task, consisting of 15-trial blocks. Participants completed 2–3 practice blocks until their mean estimation error was less than 5 for numerosity estimation or less than 25 cm^2 for area estimation. The entire experiment lasted approximately 110 minutes.

2.3 Data Analysis

Experimental data were analyzed using MATLAB R2018b. First, all trials for each participant in a single task were combined, and trials without recorded responses were excluded. According to the Weber-Fechner law, psychological representation of physical stimuli follows a logarithmic form. Therefore, we log-transformed (base 2) the numerosity, array area, and participants' estimates for all trials. To enable quantitative analysis across numerosity and area units, we further standardized the log-transformed values based on the mean and standard deviation of the physical stimuli.

To examine the influence of current relevant features, current irrelevant features, previous trial relevant features, previous trial irrelevant features, and previous trial estimates on current estimates, we constructed four GLMMs (Zhang & Luo, 2023). Based on previous literature, previous trial estimates have a consistently strong attractive effect on current estimates (Moon & Kwon, 2022; Pascucci et al., 2019). Therefore, to improve model explanatory power, we included previous trial estimates and current relevant features as independent variables in all GLMMs, with the remaining three factors entered separately into different models. Model 1 assumed that previous trial relevant features influence current estimates (i.e., serial dependence for task-relevant features). Model 2 assumed that current irrelevant features influence current estimates (i.e., cross-feature interactions within the same object). Model 3 assumed that previous trial task-irrelevant features influence current estimates (i.e., serial dependence for task-irrelevant features). Model 4 was the full model, assuming that all five factors contribute to current estimates and jointly influence participant decisions. Mixed-effects models simultaneously consider fixed effects at the group level and random effects due to individual differences between participants. Participants' estimates followed a normal distribution, Yij ~ Normal(pij). Using the numerosity task as an example, Model 4 was expressed as:

0 핒 + 1 핒 CurrentNumerosity 핒 PreviousResponse 핒 PreviousNumerosity 핒 CurrentArea 핒 + 5 핒 PreviousArea 핒; 1 핒; 2 핒; 3 핒; 4 핒; 5 핒代表第 i 个被试，代表当前任务下的第 j 个试次，代表第 i 个被试在第 j 个试次中的估计值。

2.4 Results

To compare the relative influence of current irrelevant features, previous trial relevant features, and previous trial irrelevant features on current trial perception, we combined all trials across all participants for regression analysis, constructing four GLMMs. Model 1 included previous trial relevant features, current trial relevant features, and previous trial estimates. Model 2 included current irrelevant features, current relevant features, and previous trial estimates. Model 3 included previous trial irrelevant features, current relevant features, and previous trial estimates. Model 4 included all five factors: previous trial relevant features, current irrelevant features, previous trial irrelevant features, current relevant features, and previous trial estimates. We determined the optimal model by calculating and comparing Bayesian Information Criterion (BIC) values across the four models. BIC considers both model fit and complexity, helping balance these aspects to avoid overfitting. Compared to other model selection criteria, BIC imposes a stronger penalty for complexity, thus providing more robust model selection with large sample sizes (Burnham & Anderson, 2004). As shown in Table 1 , Model 4 (the full model) performed optimally in both numerosity estimation and area estimation tasks (numerosity task: BIC values of 8533, 8158, 8589, and 8052 for Models 1–4, respectively; area task: BIC values of 11713, 10882, 11838, and 10713 for Models 1–4, respectively). This indicates that in both tasks, information from current irrelevant features, previous trial relevant features, and previous trial irrelevant features all contributed to current perceptual estimates.

We also used Mean Squared Error (MSE) as a model comparison metric (Table 2), yielding consistent results with Model 4 showing optimal performance.

Further examination of regression coefficients in the winning model (Model 4) revealed the magnitude and direction of serial dependence effects for each factor. As shown in Figure 2a [Figure 2: see original paper], in the numerosity estimation task, current numerosity (current relevant feature), array area (current irrelevant feature), and previous trial estimates all positively predicted participants' perception of the current stimulus feature (current relevant feature: $\beta = 0.76$, 95% CI = [0.75, 0.77], $t(9561) = 203.94$, $p < 0.001$; current irrelevant feature: $\beta = 0.08$, 95% CI = [0.07, 0.09], $t(9561) = 21.47$, $p < 0.001$; previous trial estimate: $\beta = 0.19$, 95% CI = [0.17, 0.21], t(9561) = 19.07, $p < 0.001$). In contrast, both numerosity and area from the previous trial showed negative relationships with current perception, indicating repulsive serial dependence effects (previous trial relevant feature: $\beta = –0.09$, 95% CI = [–0.10, –0.07], t(9561) = –10.33, $p < 0.001$; previous trial irrelevant feature: $\beta = –0.02$, 95% CI = [–0.03, –0.02], t(9561) = –6.23, $p < 0.001$).

In the area estimation task, the direction of influence for each variable was consistent with the numerosity estimation task. Current task-relevant features, task-irrelevant features, and previous trial estimates all showed positive correlations with current perceptual estimates (current relevant feature: $\beta = 0.64$, 95% CI = [0.63, 0.65], t(9553) = 149.70, $p < 0.001$; current irrelevant feature: $\beta = 0.14$, 95% CI = [0.13, 0.15], t(9553) = 32.22, $p < 0.001$; previous trial estimate: $\beta = 0.22$, 95% CI = [0.20, 0.24], t(9553) = 21.70, $p < 0.001$), while both previous trial relevant and irrelevant features produced repulsive serial dependence effects (previous trial relevant feature: $\beta = –0.11$, 95% CI = [–0.12, –0.09], t(9553) = –13.79, $p < 0.001$; previous trial irrelevant feature: $\beta = –0.02$, 95% CI = [–0.03, –0.01], t(9553) = –4.21, $p < 0.001$).

2.5 Discussion

In both numerosity and area estimation tasks, the full model performed optimally, indicating that for both numerosity and area attributes, current irrelevant features, previous trial relevant features, previous trial irrelevant features, and previous trial estimates all significantly influenced current trial perceptual decisions. These results demonstrate that different attributes of the same object influence each other during representation, and even features not explicitly attended to can affect participants' representation of current task-relevant features. Furthermore, the results show that for linearly distributed features, previous irrelevant features still produce serial dependence effects, albeit with smaller contributions than task-relevant features.

Regarding the direction of serial dependence, this study found that previous trial perceptual estimates had an attractive effect on current trial estimates, while previous trial physical features had a repulsive effect on current perception. These opposite biases may reflect processing at different levels operating on different timescales: perceptual decisions are attracted to recent perceptual decisions while being repelled from recent physical feature values (Gekas et al., 2019; Moon & Kwon, 2022; Schwiedrzik et al., 2014).

Numerosity and area are closely related attributes in magnitude perception theory. Does the serial dependence effect caused by irrelevant features stem from this specific relationship, or is it a general phenomenon across numerosity and other non-numerical attributes, such as the average size of individual dots? Average dot size is a critical statistical property that measures the retinal area occupied by dots in an array, posing greater cognitive challenges as it requires comprehensive evaluation and processing of visual input. When numerosity serves as a task-irrelevant feature, does it still influence judgments of dot size in the current trial? Conversely, when unattended dot size attributes are task-irrelevant, do they influence numerosity representation in the current trial? To investigate these questions, we designed Experiment 2.

3.1 Experiment 2 Purpose

To determine whether the effects of task relevance on serial dependence for linear features observed in Experiment 1 are specific to numerosity and area or represent a general phenomenon across linear features, Experiment 2 investigated the behavioral characteristics of serial dependence for size attributes and the modulatory role of task relevance. We continued to use estimation tasks to assess whether the serial dependence effects of task-irrelevant features observed between area and numerosity could generalize to other numerosity-related features and, if so, whether they would show consistent patterns. We hypothesized that task relevance would modulate serial dependence similarly to Experiment 1: in the numerosity estimation task, numerosity as the task-relevant feature should show stronger serial dependence, while average dot size as the task-irrelevant feature should show weaker effects, with the opposite pattern expected in the size estimation task.

3.2.1 Participants

Following the same criteria as Experiment 1, the required sample size was 29 participants. Experiment 2 actually recruited 34 participants, including 25 females with a mean age of 21.24 years. All were Beijing Normal University students with normal or corrected-to-normal vision, no color blindness or weakness, right-handed, and were not mathematics majors or psychology majors above the freshman level. The study was approved by the Experimental Ethics Committee of the Faculty of Psychology at Beijing Normal University, and participants received monetary compensation.

3.2.2 Apparatus and Materials

The experiment was conducted in a quiet, dark room. Participants viewed the screen from 55 cm. Stimuli consisted of dot arrays composed of black and white solid dots. Dot arrays were presented within a circular region centered on the screen and generated using CUSTOM, varying orthogonally in numerosity and average dot size. Arrays contained 8, 10, 12, 16, 20, 26, or 32 dots. To maintain equal luminous flux, black and white dots were equal in number, each comprising half of the total. Array area was fixed at 80.2 degree^2. Average dot size (total area of all dots divided by numerosity) had seven levels: 0.04, 0.05, 0.06, 0.08, 0.10, 0.13, or 0.16 degree^2. Individual dot area ranged from 0.25 to 1.75 times the average size. All other settings were identical to Experiment 1.

3.2.3 Experimental Design

The experiment employed a 7$×7×2 *blockdesign*, *witheachparticipantcompletingallconditions.Thethreeindep*
(1)*numerosity*, *rangingfrom*8*to*32*dotswithsevenlevels*; (2)*averagedotsize*, *rangingfrom*0.04*to*0.16*degree*^{2}
with seven levels; and (3) task relevance: in the numerosity estimation task, participants attended to numerosity (task-relevant) while size was task-irrelevant,

whereas in the size estimation task, participants attended to average dot size (task-relevant) while numerosity was task-irrelevant. Task order was counterbalanced across participants. The dependent variable was participants' estimates of the task-relevant feature.

3.3 Results

As in Experiment 1, we combined all trials for each participant within a task for regression analysis, constructing the same four GLMMs as in Experiment 1. Model selection based on BIC values again identified Model 4 as optimal in both numerosity and size estimation tasks (Table 1). Model 4's BIC values were substantially lower than the first three models (numerosity task: BIC values of 9638, 9621, 9721, and 9493 for Models 1–4, respectively; size task: BIC values of 19002, 18183, 19200, and 17936 for Models 1–4, respectively). This indicates that in both numerosity and size estimation, participants integrated information from current irrelevant features, previous trial relevant features, and previous trial irrelevant features.

Further examination of regression coefficients in the winning model (Model 4) revealed the magnitude and direction of serial dependence for each factor. Model 4 coefficients are shown in Figure 2b [Figure 2: see original paper]. In the size estimation task, consistent with Experiment 1, current task-relevant features, task-irrelevant features, and previous trial estimates all positively predicted current trial perception (current relevant feature: $\beta = 0.84$, 95% CI = [0.83, 0.85], t(9868) = 140.41, $p < 0.001$; current irrelevant feature: $\beta = 0.20$, 95% CI = [0.19, 0.21], t(9868) = 33.28, $p < 0.001$; previous trial estimate: $\beta = 0.29$, 95% CI = [0.27, 0.31], t(9868) = 30.00, $p < 0.001$), while previous trial features produced repulsive serial dependence effects (previous trial relevant feature: $\beta = –0.16$, 95% CI = [–0.18, –0.14], t(9868) = –16.43, $p < 0.001$; previous trial irrelevant feature: $\beta = –0.03$, 95% CI = [–0.04, –0.02], t(9868) = –4.50, $p < 0.001$).

In the numerosity estimation task, current numerosity and previous trial estimates both positively predicted current numerosity perception (current relevant feature: $\beta = 0.74$, 95% CI = [0.73, 0.75], t(9835) = 188.37, $p < 0.001$; previous trial estimate: $\beta = 0.22$, 95% CI = [0.20, 0.23], t(9835) = 22.29, $p < 0.001$), while current dot size negatively predicted current numerosity perception (current irrelevant feature: $\beta = –0.04$, 95% CI = [–0.05, –0.04], t(9835) = –11.21, $p < 0.001$). Previous trial numerosity showed a negative correlation with current numerosity perception, indicating a repulsive serial dependence effect for the relevant feature (previous trial relevant feature: $\beta = –0.09$, 95% CI = [–0.10, –0.07], t(9835) = –10.33, $p < 0.001$). However, previous trial dot size as an irrelevant feature produced an attractive serial dependence effect (previous trial irrelevant feature: $\beta = 0.02$, 95% CI = [0.02, 0.03], t(9835) = 5.89, $p < 0.001$). Combining results from both experiments, the influence of a stimulus feature on current trial perceptual decisions was opposite in direction to the serial dependence effect produced by that same feature from the previous trial. That is, if a feature positively predicted current perceptual estimates, it produced negative serial dependence in the subsequent trial; conversely, if it negatively predicted current estimates, it produced positive serial dependence in the subsequent trial.

3.4 Discussion

Consistent with Experiment 1, both numerosity and size estimation tasks showed attractive effects of previous trial estimates on current trial perception. Moreover, both task-relevant and task-irrelevant features from the previous trial influenced current perception. Previous trial task-relevant features produced repulsive effects on current perception. The influence of previous trial task-irrelevant features showed an asymmetry: when numerosity served as the irrelevant feature, its effect on current size perception was repulsive, whereas when average dot size served as the irrelevant feature, its effect on current numerosity perception was attractive. This asymmetry may be related to the intrinsic characteristics of the two stimulus features and their relationship.

4 General Discussion

Using numerosity perception as our research object, this study investigated the influence of task relevance on serial dependence for linear features through two experiments: numerosity and area estimation tasks (Experiment 1) and numerosity and average dot size estimation tasks (Experiment 2). In both experiments, model comparisons using GLMM consistently supported that, beyond current trial task-relevant features and previous trial estimates, current irrelevant features, previous trial relevant features, and previous trial irrelevant features all significantly contributed to current trial perceptual decisions. Further examination of regression coefficients for these factors revealed a consistent pattern across both experiments: regardless of task relevance, the influence of a feature from the previous trial on current perception was always opposite to that of the same feature in the current trial. For task-relevant features, serial dependence from the previous trial was always repulsive. For task-irrelevant features, whether the resulting serial dependence was attractive or repulsive depended on the feature's intrinsic properties: when numerosity served as the task-irrelevant feature, its serial dependence was always repulsive regardless of whether the current task-relevant feature was array area or average dot size; when array area served as the task-irrelevant feature, its serial dependence was also repulsive; however, only when average dot size served as the irrelevant feature did it produce attractive serial dependence.

The repulsive serial dependence effect of previous trial task-relevant features on current perception contrasts with the attractive serial dependence effects found in classic studies (Cicchini et al., 2018; Fischer & Whitney, 2014; Xia et al., 2016). This discrepancy likely relates to our simultaneous consideration of previous trial perceptual estimates as a factor influencing serial dependence. Previous research has found that previous trial behavioral responses and stimulus physical values differentially influence subsequent judgments, and when examined together rather than separately, they reveal substantially different serial dependence patterns (Shan & Postle, 2022; Stern et al., 2022). Pascucci et al. (2019)

found that when participants were not required to report the target in certain trials, the stimulus produced repulsive effects on subsequent perception, whereas when a perceptual report was required, the effect was attractive. Additionally, because forced-choice tasks are considered more direct measures of perception, the authors used a forced-choice task (where participants reported whether the target orientation was closer to vertical or horizontal rather than reproducing the exact orientation) and again confirmed that stimuli produced repulsive effects while responses produced attractive effects. Moon and Kwon (2022) attributed the attractive serial dependence for stimuli found in classic studies to their high correlation with participants' responses. After separately fixing perceived orientation and physical orientation, they found that when perceived orientation was fixed, physical orientation produced repulsive serial dependence while previous responses continued to show attractive effects. Sadil et al. (2021) replaced the single-factor analysis commonly used in classic serial dependence studies (considering only previous stimulus values) with a two-factor analysis that simultaneously considered both previous stimuli and responses. Reanalysis of classic study data consistently revealed repulsive effects for stimuli and attractive effects for responses. Therefore, the attractive serial dependence for stimuli reported in classic studies may be attributable to their failure to consider participants' responses from the previous trial as a factor. The evidence from these studies and our finding of repulsive serial dependence for task-relevant features support the notion that attractive effects in serial dependence primarily originate from previous trial perceptual responses, while repulsive effects primarily stem from previous trial physical feature values. The opposite directions of serial dependence at the stimulus and response levels may reflect the visual system's need to balance sensitivity to external information and dependence on past experience during stimulus processing (Pascucci et al., 2019). In perceptual and cognitive processes, we must process various stimuli while balancing sensitivity and experiential dependence. Excessive sensitivity can disrupt attention and cognition, while excessive dependence on past experience can cause neglect of new information. The balance between sensitivity and experiential dependence must be flexibly adjusted according to task demands—clear tasks require greater sensitivity, while complex tasks may benefit from greater dependence on experience. This balance can enhance perceptual and cognitive performance.

This study found that even task-irrelevant linear features exhibit significant serial dependence effects, providing support for object-level serial dependence. Objects are generally considered countable entities integrated from sets of features (Adelson & Bergen, 1991; Pascucci et al., 2023) and typically possess spatiotemporal continuity (Kahneman et al., 1992). Object files are considered fundamental units for information processing in perception, attention, and working memory. If perception is constructed on an object basis, do past perceptual experiences influence current perception at the object level or the feature level? Collins (2022a) proposed two theoretical hypotheses. The first suggests that serial dependence occurs directly at the level of basic visual features. If serial dependence operates at low-level feature processing stages, cross-feature serial dependence should not occur. The second hypothesis posits that serial dependence may occur at the object level. Attending to a single feature of an object, such as color, focuses attention while simultaneously bringing other features of that object into the attentional spotlight, thereby improving the quality and efficiency of object representation (Kahneman et al., 1992; Printzlau et al., 2022; Zhou et al., 2016). If this hypothesis holds, serial dependence for the same feature across different objects should disappear, while mutual influences should exist between different features of the same object. Object-based serial dependence has been validated in studies of circularly distributed features. Liberman et al. (2016) demonstrated object-based serial dependence using spatiotemporal continuity: they found that participants' perception of the final grating's orientation was only influenced by preceding gratings when they moved coherently across occluders, not when they moved incoherently or remained stationary on opposite sides of occluders. Kramer and Jacobson (1991) found that target search was faster and more accurate when target and distractor were on the same object versus different objects. Liberman et al. (2014) revealed that serial dependence occurs even when object identity remains constant while its features change, such as when viewing faces from different angles. Additionally, changes in face gender were found to significantly reduce serial dependence for facial expression when participants judged whether faces showed disgust or happiness (Collins, 2022a). Furthermore, Fritsche and de Lange (2019) found that although serial dependence for current grating orientation was reduced when the previous task required size judgment versus orientation judgment, it remained significant. This indicates that even when task demands require selective attention to a specific target feature (e.g., size), other features belonging to the same object (e.g., orientation) are not completely filtered out despite being task-irrelevant, but rather continue to be perceived or remembered, thereby influencing subsequent stimulus processing. These studies collectively support the existence of object-based serial dependence.

We found that although task-irrelevant linear features exhibit serial dependence, the effect is significantly smaller than for task-relevant features, consistent with previous findings on how attention or task relevance modulates serial dependence for circular features. Flesch et al. (2022) investigated neural representations in frontal-parietal cortex when leaf shape and branch bifurcation count served as task-relevant or irrelevant features, finding that irrelevant features showed compressed representations with high similarity between different feature levels, while relevant features showed more distinct representations across levels. This may occur because compressing irrelevant feature representations into a low-dimensional space reduces redundant information and interference, thereby improving feature discriminability and robustness, allowing the brain to process tasks more efficiently and stably.

The differing directions of serial dependence for task-irrelevant features indicate that these effects are also closely related to the intrinsic characteristics of the features themselves. The study found that when numerosity served as the task-irrelevant feature, its serial dependence was always repulsive regardless of whether the current task-relevant feature was array area or average dot size. When array area served as the task-irrelevant feature, its serial dependence was also repulsive. However, only when average dot size served as the irrelevant feature did it produce attractive serial dependence. A consistent finding across all tasks was that although the direction of serial dependence from previous trial irrelevant features varied by feature, it was always opposite to the direction of their influence when serving as current trial irrelevant features. The serial dependence effect from previous trial irrelevant features may be related to how features interact. For example, when a task-irrelevant feature like area covaries positively with numerosity in numerosity space (DeWind et al., 2015), its influence on numerosity is attractive in the current trial but repulsive in the previous trial. Conversely, when a task-irrelevant feature like average size covaries negatively with numerosity in numerosity space (DeWind et al., 2015), its influence is repulsive in the current trial but attractive in the previous trial. However, verification of this hypothesis and its specific mechanisms await further research.

Previous studies have also found that the characteristics of irrelevant features themselves or their relationships with relevant features influence serial dependence. Liberman et al. (2018) found that serial dependence in emotion judgment disappeared when face gender changed but remained when face race changed, suggesting that gender differences create greater dissimilarity between faces than race differences. In Fornaciai and Park's (2019a) study, although numerosity and flash count showed attractive serial dependence, numerosity and spoken count did not produce significant cross-feature serial dependence when each served as the task-irrelevant feature. Additionally, when background color changes were task-irrelevant, serial dependence was unaffected by background features, with current orientation decisions being independent of color changes in the stimulus background and systematically biased only toward the previous stimulus's orientation (Fischer et al., 2020). Feature processing relationships can be categorized as independent or integrated representation (Leibovich et al., 2017; Lourenco & Aulet, 2023). Independently processed features show perceptual independence across feature dimensions, meaning we can process different features of an object—such as color, shape, size, and orientation—separately. In studies where orientation and size have independent processing mechanisms mediated by different brain regions, no cross-feature serial dependence occurs between them. In contrast, evidence from neuroimaging, computational modeling, visual illusions, and psychophysics demonstrates that non-numerical magnitudes such as cumulative area are encoded together with number and persist throughout visual perception. Their interactions may influence number perception itself—for example, perceived numerosity may be affected by object size or shape (Harvey et al., 2015). When these features serve as task-irrelevant attributes, they continue to influence serial dependence for task-relevant features. Therefore, when investigating how task relevance influences serial dependence, whether features have independent processing mechanisms is an important factor affecting the direction of these effects.

In summary, this study explored how task relevance influences serial dependence for linearly distributed features. The results demonstrate that previous irrelevant features exhibit serial dependence effects, though these are weaker compared to task-relevant features. This finding reveals mutual influences between perceptual representations of different attributes within the same object, showing that even features not explicitly attended to can affect perception of current task-relevant features. Moreover, the existence of cross-feature serial dependence supports the hypothesis that serial dependence can occur at the object level. Future research could combine functional magnetic resonance imaging and other techniques to further explore the neural basis of cross-feature serial dependence in numerosity perception and investigate the representational mechanisms underlying these effects.

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