

Attractive and repulsive serial dependence: The role of task relevance, the passage of time, and the number of stimuli

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Visual decisions are attracted toward features of previous stimuli. This phenomenon, termed *serial dependence*, has been related to a mechanism that integrates present visual input with stimuli seen up to 10 to 15 s in the past. It is believed that this mechanism is “temporally tuned” and the effect of prior stimuli fades with time. Here, we investigated whether the temporal window of serial dependence is influenced by the number of stimuli shown. Observers performed an orientation adjustment task where the interval between the past and present stimulus and the number of intervening stimuli varied. First, we found that the direction—repulsive or attractive—and duration of the effect of a past stimulus depends on whether the past stimulus was relevant to behavior. Second, we show that the number of stimuli, and not only the passage of time, plays a role: The effect of a stimulus at a fixed interval depends on the number of other stimuli shown after. Our results demonstrate that neither a single mechanism nor a general tuning window can fully capture the complexity of serial dependence.

Introduction

Perceptual decisions depend not only on the characteristics of the stimulus available at the moment but also on the history of events before. For example, decisions about the orientation of a visual stimulus can be systematically biased by the orientation of stimuli seen a few seconds before, a phenomenon known as *serial dependence* (Fischer & Whitney, 2014).

Studies over the past decade have reported serial dependence in a variety of visual tasks (Kiyonaga et al., 2017; Pascucci et al., 2023), showing effects that last approximately 10 to 15 s and decline as a function of time: A stimulus presented 5 s before has a stronger influence on current decisions than a stimulus presented 10 s before (Fischer & Whitney, 2014; Manassi et al., 2018, 2019). In most of these studies, serial dependence is *attractive*, which means that present stimuli are judged

as more similar to previous stimuli than they truly are. The time course of this attractive bias has been often related to the temporal tuning of a mechanism, termed *continuity field* (Collins, 2019; Fischer & Whitney, 2014), which integrates prior and current visual input, exploiting the seconds-long autocorrelation of events in the natural world (Kalm & Norris, 2018; van Bergen & Jehee, 2019). The consistency of the temporal tuning window of serial dependence has been considered a hallmark or a defining criterion of continuity fields (Manassi et al., 2019).

Most of the findings on serial dependence, however, come from paradigms in which 10 to 15 s correspond to two to three stimuli, shown on consecutive trials. This leaves it unclear whether the temporal window of serial dependence would change depending on the number of presented stimuli (Fischer & Whitney, 2014; Manassi et al., 2019, 2021). That is, the influence of a stimulus presented 10 s before might change depending on how many other stimuli are presented in between.

Previous work on the temporal dynamics of serial dependence has mostly focused on the effect of the passage of time. For instance, it has been shown that the bias toward prior stimuli increases with the intertrial interval and with the interval before the current stimulus is reported (Bliss et al., 2017; Fritzsche et al., 2017; see also Bilacchi et al., 2022). Such findings indicate that the strength of serial dependence varies during working memory intervals but cannot tell whether the number of stimuli plays a role. Other studies have found attractive biases toward decisions made in the past, even when increasing the number of stimuli between the current and the previous decision (Pascucci et al., 2019; Pascucci & Plomp, 2021). Crucially, these works have shown that stimuli presented—but not reported—in the interval between perceptual decisions can cause systematic repulsive and not attractive biases, suggesting that, at least under some conditions, the direction and temporal dynamics of serial dependence are largely dictated by the structure of the task at hand.

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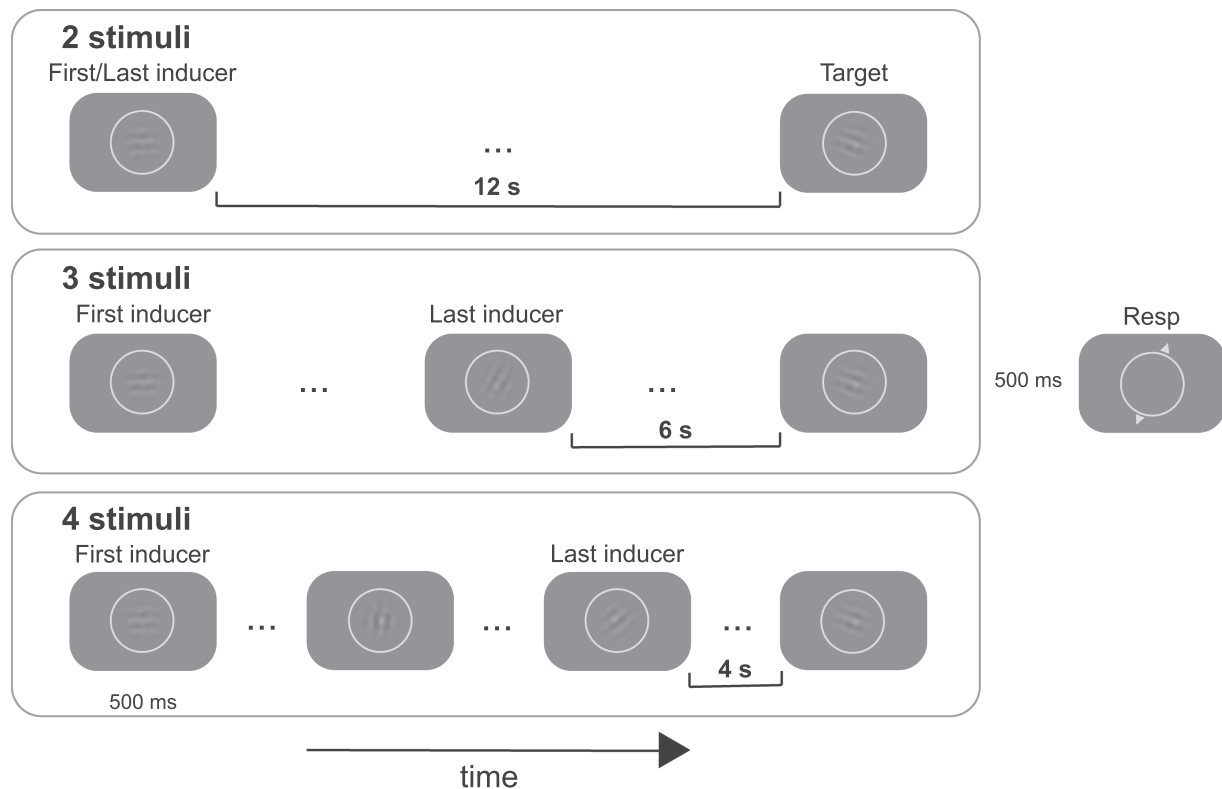


Figure 1. Stimuli and paradigm in Experiment 1. On each trial, observers were presented with a sequence of Gabor stimuli (inducers) and reproduced the orientation of the last one (target). A single trial could contain two, three, or four stimuli. Stimuli were presented inside a placeholder (white circular frame) and the response was made by adjusting the orientation of an imaginary line connecting two triangles at the extremities of the circular frame. Stimuli are not drawn to scale.

Studies investigating the role of task relevance have also shown that not all the stimuli falling within the temporal window of serial dependence are necessarily integrated. For instance, [Fischer et al. \(2020\)](#) presented participants with two clouds of moving dots in different colors on each trial, displayed in succession. A postcue indicated which of the two clouds, based on either color or serial position (e.g., the “context” feature), they were to reproduce the motion direction of. Serial dependence in reporting motion directions was highest between trials for stimuli with a matching context feature but only when that feature was important for the task at hand (e.g., for stimuli with the same color when color was the relevant feature cued on consecutive trials). Similarly, [Ceylan et al. \(2021b\)](#) presented observers with two overlaid features, a cloud of moving dots and an oriented Gabor, and found that only the feature cued and reported on the previous trial induced serial dependence on the following trial. Moreover, there is extensive evidence that attention to the previous stimulus, due to its relevance for the task, is a prerequisite of many forms of serial dependence reported in the literature ([Fischer & Whitney, 2014](#); see [Pascucci et al., 2023](#), for a review). In agreement with several other findings ([Feigin et al.,](#)

[2021](#); [Pascucci et al., 2019](#); [Pascucci & Plomp, 2021](#); but see [Fornaciai & Park, 2018](#); [Murai & Whitney, 2021](#)), these works suggest that, within the time window in which serial dependence is typically found, there can be strong modulations of the effect due to the behavioral relevance of prior stimuli.

None of the above studies, however, has presented a systematic investigation of the relationship between the number of stimuli and the interval of time, a critical aspect in understanding the temporal dynamics of serial dependence.

To this end, we performed two experiments, using a modified version of the standard orientation adjustment task. In both experiments, we varied the number of intervening stimuli and the time interval between a stimulus shown in the past and the stimulus that participants had to reproduce in the present (see [Figure 1](#)). If serial dependence is exclusively a function of time, the stimulus shown at a given interval in the past should always produce the same bias, independently of how many other stimuli are presented in between.

Overall, we found that, in addition to the passage of time, two main factors play a role: the relevance of the previous stimulus to the task and the number of

intervening stimuli. We discuss how all these factors together contribute to serial dependence—that is, the bias eventually measured in behavioral reports, beyond a single mechanism and a general tuning window.

General methods

Ethics statement

The study was approved by the local ethics committee in accordance with the Declaration of Helsinki (except for preregistration) ([World Medical Organization, 2013](#)).

Apparatus

All experiments were run on a gamma-corrected VG248QE monitor (resolution: $1,920 \times 1,080$ pixels, refresh rate: 120 Hz) in a darkened room. Stimuli were generated with custom-made scripts written in MATLAB (R2013a) and the Psychophysics Toolbox and presented on a gray background (62.66 cd/m^2). Participants sat at 57 cm from the computer screen, with their head on a chinrest.

Participants

We recruited 20 healthy participants (12 females, age range of 18–35 years) for Experiment 1 and 20 participants (11 females, age range of 18–35 years) for Experiment 2. All participants had normal or corrected-to-normal vision according to the Freiburg Visual Acuity test (Bach, 1996) and were paid (20 CHF/h) after completing the experiments. Written informed consent was collected from all participants in advance.

Stimuli and procedures

Experiment 1

Figure 1 illustrates the sequence of events in one trial of Experiment 1. Each trial started with a placeholder (a white circular frame with a diameter of 7°), indicating the upcoming stimulus location, which lasted until the end of a response. After 1,000 ms, a Gabor stimulus (noise: 50%, peak contrast: 25% Michelson, spatial frequency: $0.75 \text{ cycle/}^\circ$, Gaussian envelope: 1.5°) was presented inside the placeholder for 500 ms. Depending on the number of stimuli within the trial (two, three, or four), the next Gabors appeared with an interstimulus interval (ISI) of 12, 6, or 4 s. Following

the last Gabor and an interval of 500 ms, a response tool was presented. The response tool was made of two small triangles placed at the opposite ends of the placeholder, drawing an imaginary line. Participants rotated the response tool to reproduce the orientation of the last Gabor by moving a computer mouse upward (clockwise rotation) or downward (counterclockwise rotation) and clicking the left mouse button to confirm the final decisions. The subsequent trials started after a random intertrial interval (1,000–2,000 ms).

In regular trials (80%), the time interval between the first and the last Gabor was always between 12 and 13 s. To reduce the expectations on the trial sequence and to preserve attention on each Gabor, we included catch trials (20%) in which the sequence could stop earlier (e.g., after one, two, or three stimuli) and the responses were collected right after the sequence ended. Stimulus orientations were assigned randomly ($0\text{--}179^\circ$, in steps of 15° , jittered $\pm 7^\circ$).

Before the experiment, all participants were provided written and verbal instructions. To ensure that participants understood the task, they performed two blocks of four practice trials under the supervision of the experimenter. The experiment consisted of eight blocks of 26 trials each, for a total of 208 trials, and lasted approximately 1 hr.

Experiment 2

In Experiment 2, trials consisted of a single Gabor, or two Gabor stimuli sequentially presented. In trials with two stimuli, the ISI between the two and the delay following the last Gabor and before the response was 2,000 ms. As in the first experiment, participants reproduced the orientation of the last Gabor by rotating the response tool. In Experiment 2, we removed the placeholders and used a response bar for a simplified design. To facilitate the attractive bias to the past, we used noise-free Gabor stimuli with lower contrast (peak contrast: 15% Michelson) and lower spatial frequency ($0.56 \text{ cycle/}^\circ$), in line with parameters used in prior studies ([Cicchini et al., 2018](#); [Manassi et al., 2018](#)). Similarly, to achieve a complete picture of the direction and strength of these biases across the entire orientation distance range, as typically done in prior work, we used orientation distances in the $\pm 90^\circ$ range. In this experiment, we set the number of catch and regular trials to the same proportion (50% each), to ensure that participants were not paying more attention to the second Gabor, because it was more likely to be the target. In the catch trials, the response tool was presented following the first Gabor and a delay of 2,000 ms.

After written and verbal instructions, participants performed eight practice trials under the experimenter's supervision before starting the experiment. The

experiment consisted of 10 blocks of 30 trials each, for a total of 300 trials, and lasted approximately 45 min.

Analysis

Before data analyses, we excluded trials with high adjustment errors (larger than 45°) or slow adjustment times (longer than 10 s). Following the first outlier removal, trials with adjustment errors of more than 1.5 interquartile ranges above the upper quartile or below the lower quartile were further removed. Additionally, two participants were excluded in the first experiment, one showing strong repulsive effects in all conditions, with values larger than 3 standard deviations from the average bias of the group, the other showing poor performance (a standard deviation of errors before cleaning larger than 45° and more than 20% of outlier trials). Participants performed the task with an average absolute error of $6.07 \pm 1.06^\circ$ and average reaction times of 1.92 ± 0.55 s in Experiment 1 and an average absolute error of $7.36 \pm 1.06^\circ$ and average reaction times of 1.73 ± 0.42 s in Experiment 2.

To quantify serial dependence, we used a “model-free” approach (Ceylan et al., 2021a; Samaha et al., 2019) in the analyses of both experiments. In Experiment 1, for each participant, we first binned the adjustment errors based on the acute angle distance between the previous and the present orientations (Δ) as “close” ($1\text{--}25^\circ$) and “far” ($26\text{--}50^\circ$). In Experiment 2, Δ distances ranged between -90° and 90° ; therefore, we binned the adjustment errors for the distances as “close” ($1\text{--}30^\circ$), “mid” ($31\text{--}60^\circ$), and “far” ($61\text{--}90^\circ$). Then, we subtracted the averaged errors for positive orientation distances from those for negative orientation distances within each bin. In this way, for each participant and bin, we estimated the magnitude of the serial dependence bias, representing the deviation of the errors toward (attractive bias) or away (negative bias) from the previous orientation. The estimated biases were submitted to repeated-measures ANOVA and paired Student *t*-tests for the statistical analyses (see Results). This nonparametric approach was preferred over widely used model-fitting approaches because it considers both attractive effects, typically larger for small orientation differences, and repulsive effects, which become more evident for larger orientation differences (Fritsche & de Lange, 2019). For statistical reports, *p*-values are reported up to the third decimal.

In the analysis of interindividual differences in Experiment 1, we considered the bias for the close orientation distance bin as a function of the inducer presented at the 4-s ISI. The bias was used to predict the effect of the previous target at close orientation bins, by means of linear regression. The averages shown at 6 s and 12 s ISI are biases at close orientation distances for the two inducers shown before the 4 s ISI inducer in

trials where the sequence contained four stimuli (e.g., three inducers and one target).

Results

Experiment 1

Observers were presented with a sequence of oriented Gabor stimuli and reproduced the orientation of the last one (see Figure 1). On each trial, two, three, or four Gabors were presented one after the other. In the condition with two stimuli, the ISI was 12 s. In the condition with three and four stimuli, the ISI between each stimulus was 6 and 4 s, respectively. Hence, the last Gabor (e.g., the one they had to respond to) was always presented at least 12 s from the first one but with a different number of stimuli and ISI in between. We will refer to the last Gabor as *target* and to the nonreported stimuli in the sequence as *inducers*. By *last inducer*, we refer to the inducer directly preceding the target, without other stimuli in between. By *first inducer*, we refer to the inducer at the beginning of the sequence, which could or could not be followed by other inducers. These definitions held for 80% of the trials. In the remaining 20% of “catch” trials, the sequence was interrupted randomly, and observers reported the orientation of one of the inducers (the first, second, or third, randomly selected). Catch trials were included to avoid observers focusing exclusively on the last part of the trial. In catch trials, adjustment responses were slightly less precise compared to regular trials (group-average standard deviation [σ] of the errors in regular trials: 7.48° , σ in catch trials: 8.16° , $t(17) = -3.03$, $p = 0.007$, $d' = 0.71$).

In the analysis of serial dependence, we focused on (a) the effects of previous targets and inducers, (b) the effect of the number of intervening stimuli, and (c) the effect of the passage of time (ISI) in the absence of intervening stimuli.

Effect of targets and inducers

Overall, errors were systematically biased toward the orientation of the previous target, showing the typical pattern of attractive serial dependence: Errors were more clockwise when the previous target orientation was clockwise to the present one and the other way around when counterclockwise. Conversely, the effect of inducers was reversed: Inducers caused a strong repulsive effect, particularly when the orientation difference between the inducer and the current target was large (see Figure 2A).

To statistically compare the influence of the previous target and the last inducer, we computed a measure of bias at two orientation distance bins

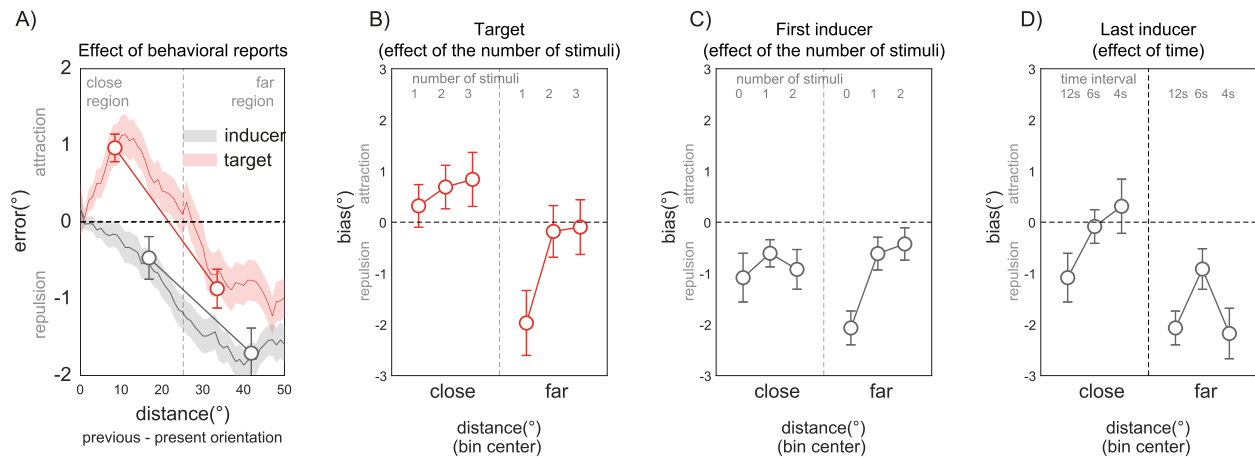


Figure 2. Results of Experiment 1. (A) Serial dependence is attractive when measured on the previous target orientation (red curve) and repulsive for the inducers' orientation (gray curve). Continuous lines with shadow bars are the running average with one standard deviation computed at the group level (Ceylan et al., 2021a). Dots represent the approximation of the curve by binning the bias at the two orientation distances (close and far regions). The inducer condition in this first plot includes the effect of all the inducers presented immediately before the target; the target condition includes the effect of all the targets reported on the previous trial, including catch trials. (B) The bias from the previous target's orientation as a function of the orientation distance (bins) to the current target and the number of intervening stimuli (1, 2, 3). (C) The bias from the first inducer presented at the beginning of the sequence as a function of the orientation distance to the target and the number of additional inducers presented before the target. (D) The bias from the last inducer in the sequence as a function of the time (ISI) between the last inducer and the target. Error bars are standard errors of the mean (SEM). Note that, except for A, catch trials were excluded from the rest of the analyses and plots.

(see Figure 2A and Methods). We submitted the bias to a repeated-measures ANOVA with factors Distance (close vs. far) and Stimulus type (target [including also the target in catch trials] vs. inducer [including all inducers shown immediately before the target]), revealing a significant main effect of Distance ($F(1, 17) = 40.66, p < 0.001, \eta_p^2 = 0.71$) and a main effect of Stimulus type ($F(1, 17) = 14.73, p = 0.001, \eta_p^2 = 0.46$) without an interaction between the two ($F(1, 17) = 2.07, p = 0.17, \eta_p^2 = 0.11$). The bias due to the previous target orientations was positive (e.g., attractive) for close orientation distances ($t(17) = 5.36, p_{holm} < 0.001, d' = 1.26$, paired t -test vs. 0) and negative when orientations were far ($t(17) = -3.46, p_{holm} = 0.006, d' = 0.82$), in line with previous findings (Fritsche & de Lange, 2019). Conversely, the bias due to the last inducer orientation was strongly repulsive for far orientation distances ($t(17) = -5.26, p_{holm} < 0.001, d' = 1.24$) but absent for close orientation distances ($t(17) = -1.70, p_{holm} > 0.05$).

Effect of the number of intervening stimuli

We then focused on the effect of the targets and inducers as a function of the number of intervening stimuli. In the analysis of serial dependence from the previous target (including only the targets in regular trials), a repeated-measures ANOVA with factors Distance (close vs. far) and Number of stimuli (1, 2,

3) revealed a significant main effect of Distance ($F(1, 17) = 12.85, p = 0.002, \eta_p^2 = 0.43$) and of Number of stimuli ($F(2, 34) = 3.95, p = 0.028, \eta_p^2 = 0.19$) but no interaction ($F(2, 34) = 0.90, p = 0.42, \eta_p^2 = 0.05$; Figure 2B).

In the analysis of serial dependence from inducer stimuli in regular trials, we considered the bias due to the very first stimulus in the sequence (*first inducer*, see Figure 2C), as a function of the number of stimuli that occurred after (0, 1, 2). A repeated-measures ANOVA revealed only a main effect of the Number of stimuli ($F(2, 34) = 4.00, p = 0.027, \eta_p^2 = 0.19$) but no main effect of Distance or interaction (both $p > 0.05$).

Effect of the passage of time (ISI)

We further evaluated the effect of the ISI between the last inducer and the current target in regular trials, in the absence of other intervening stimuli (Figure 2D). A repeated-measures ANOVA with factors Distance (close vs. far) and ISI (12, 6, 4 s) revealed a significant effect of both Distance ($F(1, 17) = 20.57, p < 0.001, \eta_p^2 = 0.55$) and ISI ($F(2, 34) = 3.94, p = 0.029, \eta_p^2 = 0.19$), with no interaction between the two ($F(2, 34) = 3.02, p = 0.062, \eta_p^2 = 0.15$).

The main results of the analyses reported above can be summarized as follows: (a) Inducers caused repulsive

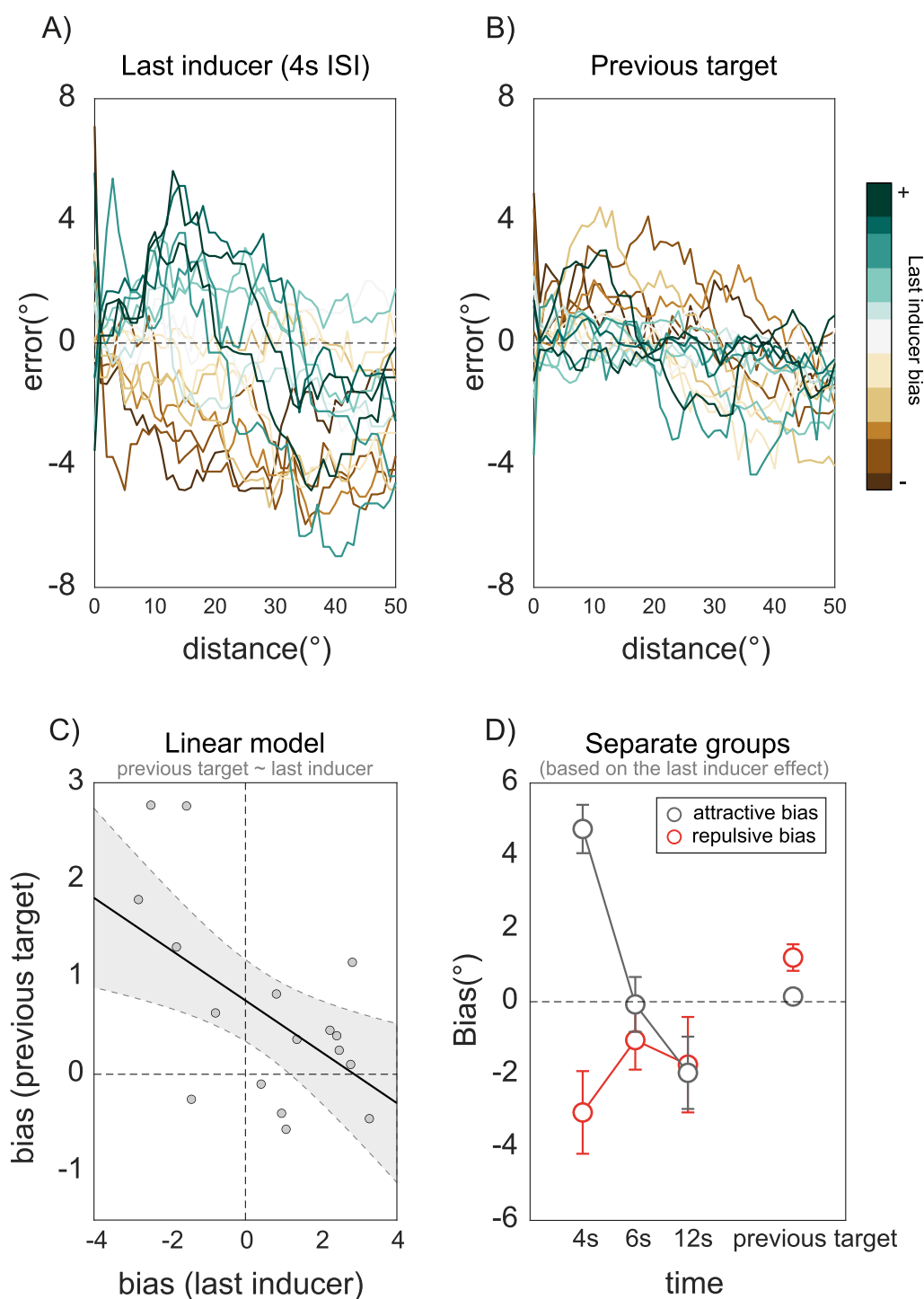


Figure 3. Results of the interindividual analysis in Experiment 1. (A) When considering the effect of the inducer presented 4 s before, individual patterns show clear variability, from strong attraction to repulsion. (B) At the individual level, the direction and strength of the effect of the inducer 4 s before were inversely related to the effect of the previous target. The curves in A and B are individual moving averages (window size = 21°). The color scale is based on the direction of the effect of the inducer: Strong attraction corresponds to the dark green extremity of the scale and strong repulsion to the brown extremity. The ordering of colors in B is based on A, to highlight the inverse relationship. (C) Predictions and confidence intervals of a linear model explaining the bias due to the previous target with the bias due to the inducer 4 s before the current target. The data points are individual biases for close distances only. (D) Plot of two separate groups of observers depending on the effect, attractive or repulsive, of the last inducer.

biases; targets caused attractive biases (Figure 2A). (b) Both attractive and repulsive biases were influenced by the number of stimuli: With more intervening inducers, the attractive bias toward previous targets increased, while the repulsive bias of the very first inducer decreased (Figures 2B,C). (c) Inducers closer in time to the current target caused less repulsion and a tendency toward attraction (Figure 2D).

Interindividual differences

Focusing on this last result, we investigated whether the decrease of repulsive biases for inducers presented 4 s before the current target could actually reflect an increase in the attractive component tied to these stimuli. A clear difference between targets and inducers is that target stimuli were behaviorally relevant and required an adjustment response. If the relevance of the stimulus is the determinant of the direction of the bias, some participants might have expected the inducers at the end of the trial—that is, close to the moment of the target, to be target stimuli, strengthening their positive effect on future decisions.

To evaluate this, we explored interindividual differences in the direction of the effect of the most recent inducer. We found large interindividual variability in the effect of the inducer presented 4 s before, with individual patterns going from strong attraction to repulsion (Figure 3A). At the individual level, the direction and strength of this bias were inversely related to the effect of the previous target (Figure 3B). Observers showing larger attractive biases toward the most recent inducer were less influenced by the previous target. Observers showing strong repulsion from the inducer were more attracted by the previous target's orientation (slope of a linear model predicting the previous target effect at close distances with the strength of the inducer effect at close distances: -0.263 ± 0.08 , $p = 0.009$, $R^2 = 0.35$, Figure 3C). Also, for the subset of observers showing strong attractive

biases toward the inducer at 4 s ISI, the bias quickly turned into repulsion for the other inducers presented at 6 and 12 s ISI (Figure 3D).

Experiment 2

A clear result in Experiment 1 is the repulsive effect of inducers. One explanation is that observers paid less attention to inducers, expecting the target to occur later, as evident from the poorer performance in catch trials. Repulsive biases have been often reported as a consequence of reduced attention to the previous stimulus (Fischer & Whitney, 2014; Fornaciai & Park, 2019; Pascucci et al., 2019; Rafiei et al., 2021). To ensure that participants were equally attending to inducers and targets, in Experiment 2, we presented only one (a single target) or two stimuli on each trial (an inducer followed by a target). Hence, each stimulus had a 50% probability to be the target (see Figure 4). To further minimize repulsive effects, we also decreased the contrast, spatial frequency, and duration of the stimulus while increasing the stimulus–response interval (Bliss et al., 2017; Ceylan et al., 2021a; Cicchini et al., 2018; Manassi et al., 2018).

The standard deviation of errors in trials with only one target stimulus (group-average σ of errors: 9.67°) was still slightly but significantly larger compared to trials where the target was preceded by an inducer (group-average σ of errors: 8.68° , $t(19) = -4.85$, $p < 0.001$, $d' = 1.08$).

In the analysis of serial dependence, we computed the bias at three orientation distance bins (see Methods). First, we evaluated the effect of targets and inducers. A repeated-measures ANOVA revealed a significant main effect of Distance ($F(2, 38) = 6.75$, $p = 0.003$, $\eta_p^2 = 0.26$) and a main effect of Stimulus type (target vs. inducer, $F(1, 19) = 21.64$, $p < 0.001$, $\eta_p^2 = 0.53$) as well as an interaction between the two ($F(2, 38) = 6.48$, $p = 0.003$, $\eta_p^2 = 0.25$). In line with the results

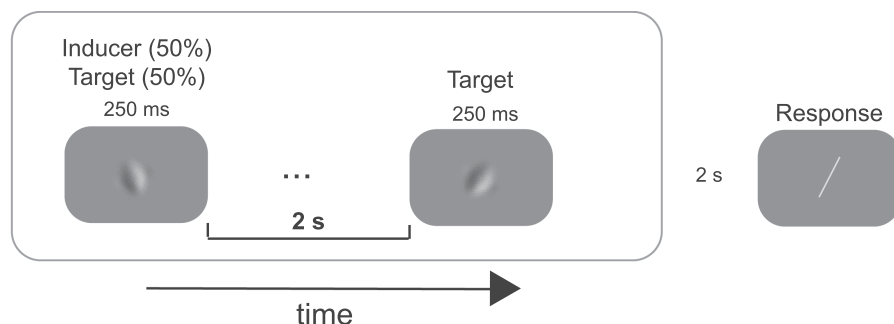


Figure 4. Stimuli and paradigm in Experiment 2. On each trial, observers were presented with only one or two Gabor stimuli. When there were two stimuli, observers had to reproduce the orientation of the second. Stimuli were shorter in duration and lower in contrast and spatial frequency compared to Experiment 1. Stimuli are not drawn to scale.

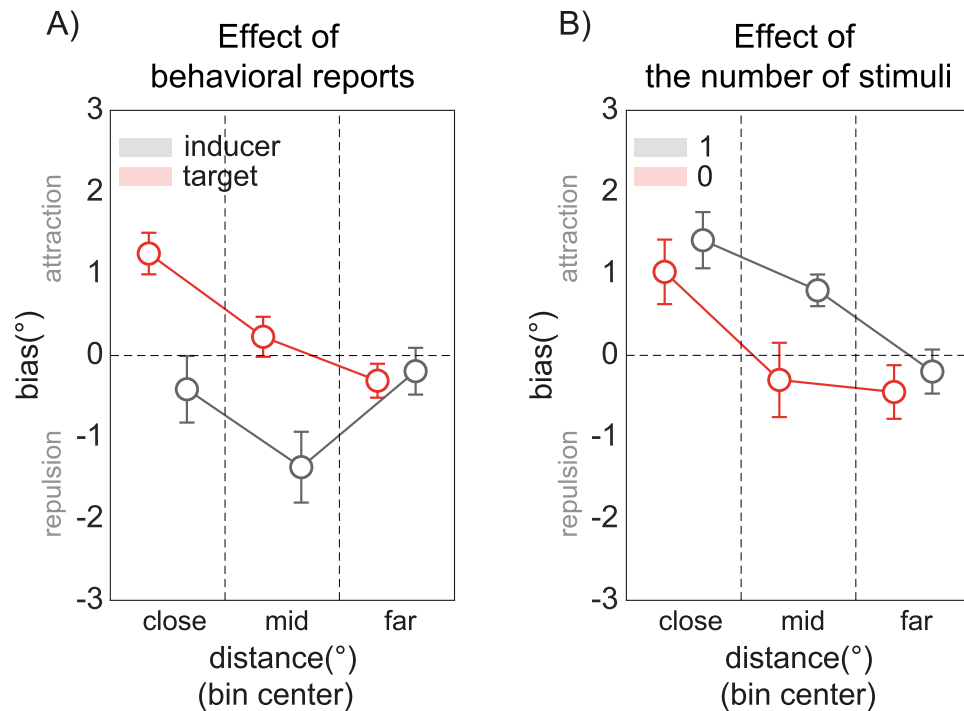


Figure 5. Results of Experiment 2. (A) As in Experiment 1, the inducer (nonreported) stimulus caused a repulsive bias (gray dots and line); the previous target caused an attractive bias (red dots and line). (B) The attractive bias toward the previous target increased when the current trial contained an inducer (gray dots and line) compared to when it contained only one target (red dots and line). Error bars are SEM.

of Experiment 1, errors were attracted toward previous targets and repelled away from the inducer (Figure 5A).

Second, we evaluated whether the attractive bias was modulated by the presence of an inducer, shown after the previous target. According to the results of Experiment 1, intervening inducers should increase the attractive bias toward previous targets. A repeated-measures ANOVA with factors Distance and Number of stimuli revealed a significant main effect of Distance ($F(2, 38) = 13.42, p < 0.001, \eta_p^2 = 0.41$) but no main effect of Number of stimuli or interaction (both $p > 0.05$; Figure 5B). Further exploratory t -test analysis motivated by the results of Experiment 1, however, revealed a significant difference in the “mid” orientation distance bin, where the attraction toward the previous target was larger if the previous target was followed by an inducer ($t(19) = -2.32, p_{holm} = 0.047, d' = 0.52$; other differences at “close” and “far”, $p_{holm} > 0.05$, one-tailed t -test, testing the hypothesis of a difference larger than 0). Hence, although the effect of intervening inducers was not evident across all distance bins, the direction of the effect for the “mid” distance bin was coherent with the results of Experiment 1.

Discussion and conclusions

We investigated serial dependence as a function of the time interval and number of stimuli between the current and previous stimulus. In two experiments, observers reproduced the orientation of a stimulus (target) shown after a sequence of other stimuli with a variable number and ISI (inducers).

One of the main results of this study, confirmed in both experiments, is the opposite effect of targets and inducers. Targets caused attraction, whereas inducers caused repulsion, despite being the same stimulus (e.g., a Gabor). Continuity fields predict only attractive biases because similar stimuli are integrated over time, independently of the task (Collins, 2019; Fischer & Whitney, 2014). Clearly, such a prediction fails to explain the present results.

What is the nature of the repulsive bias? Several studies suggest that the direction of serial dependence (i.e., repulsive or attractive) depends on attention (for a review: Pascucci et al., 2023). When the previous stimulus is not attended to, the bias is repulsive (Fischer & Whitney, 2014; Fornaciai & Park, 2019; Pascucci et al., 2019; Rafei et al., 2021). In our paradigm,

particularly in Experiment 1, observers might have paid less attention to inducers at the beginning of the trial, leading to poorer performance in catch trials and a negative bias from these stimuli. Note that, compared to other studies where repulsive biases were induced by completely and explicitly unattended stimuli (Fischer & Whitney, 2014), participants in our paradigm were instructed to pay attention to the inducers because of catch trials. Indeed, the difference in performance between catch and regular trials was only on the order of 1°, indicating that inducers were still attended to and remembered, even though with less precision than the target in regular trials.

Another possibility is that, while initially attended to, stimuli that require no response (i.e., like the inducers used here) are actively removed from working memory (Shan & Postle, 2022). Although the underlying mechanisms are still debated (Fulvio & Postle, 2020), the consequence of active removal might be a systematic bias away from the previous stimulus, consistent with the one observed in our experiments (Fritsche et al., 2020; Shan & Postle, 2022). Alternatively, it is also possible that stimuli requiring no response are implicitly used as a reference for future decisions, leading to reference-repulsion effects (DeCarlo & Cross, 1990; Stewart et al., 2005).

Under the present paradigm, we cannot disambiguate the exact origins of the repulsive bias. Nevertheless, in this and similar experiments, the direction of serial dependence effects depends strongly on whether the previous stimulus required a response (Pascucci et al., 2019; Pascucci & Plomp, 2021). We propose that the switch of the bias, from repulsive to attractive, has to do with the maintenance and active recall of prior stimulus information when an impending task is expected (Fischer et al., 2020; Pascucci et al., 2019). This, and only this, can explain why the target orientation, reported far back in time and followed by other stimuli, was the only orientation causing an attractive bias.

While inducers shown at the beginning of the trial caused systematic repulsion, we found clear interindividual variability in the effect of the inducer presented 4 s before the target. This finding adds to a body of evidence showing considerable interindividual variability in the direction of serial dependence effects (Bliss et al., 2017) as well as in the effect of prior stimuli and responses (Glasauer & Shi, 2022; Zhang & Alais, 2020). In the specific context of our task, it is plausible that the source of this interindividual variability was the degree to which different participants expected the target to occur later. Those employing such a strategy might have considered inducers occurring later (i.e., 4 s before the target) as potential targets, leading to an increase of the attractive bias.

At the group level, the attractive bias toward the inducer at 4 s ISI was inversely related to the effect of

the target on the preceding trial. Participants showing strong attractive biases toward the inducer showed no effect of the previous target. Participants showing only repulsive effects showed stronger attraction toward the previous target (Figure 3D). This indicates that attractive serial dependence is a function of the number of stimuli exerting an attractive bias within a given time window: The attractive bias of a stimulus shown more than 12 s before decreases if a new and more recent stimulus also exerts an attractive bias.

The primary interest of this work was on the temporal dynamics of serial dependence, considering the role of the passage of time and the number of intervening stimuli. It is generally believed that both time and intervening stimuli reduce the effect of prior information (Kanai et al., 2007). Here, however, we report a case of the opposite: In serial dependence, intervening stimuli can actually boost the influence of stimuli shown far back in time. In both our experiments, intervening inducers increased the attractive bias toward the previous target (Figures 1B and 5B), a finding that has not been reported before. We argue that this is due to the additive coexistence of repulsive and attractive biases: Additional stimuli carrying only repulsive effects (e.g., the inducers) nullify and flatten the repulsive component tied to the previous target, eventually increasing the attractive bias toward the previous target.

In sum, we showed that the temporal dynamics and direction of serial dependence effects are nontrivial aspects that depend largely on the details of the task. Existing studies have reported purely attractive (Ceylan et al., 2021; Fischer & Whitney, 2014; Fornaciai & Park, 2018; Manassi et al., 2018; Murai & Whitney, 2021), purely repulsive (Bae & Luck, 2019, 2020; Fornaciai & Park, 2019), or a mixture of attractive and repulsive serial dependence (Bliss et al., 2017; Fritsche & de Lange, 2019; Pascucci et al., 2019; Pascucci & Plomp, 2021). In most of these studies, the stimulus was always presented and reproduced at relatively fixed temporal intervals (e.g., every 4–5 s). By varying the frequency of stimuli and reports, we found an interplay between repulsive and attractive biases. Our findings demonstrate that, even in simple tasks where the same stimulus is shown at consecutive moments in time, the direction of serial dependence is dictated by the balance between these opposing biases. The effects that are ultimately measured in behavior (i.e., serial dependence) are modulated by the relevance of the stimulus to the ongoing task, the passage of time, and the number of intervening stimuli and cannot be reduced to a single mechanism or a general temporal tuning window of integration in vision.

Keywords: serial dependence, task relevance, negative aftereffects, sequential effects, opposite history biases

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References

- Bae, G. Y., & Luck, S. J. (2019). Reactivation of previous experiences in a working memory task. *Psychological Science*, 30(4), 587–595, <https://doi.org/10.1177/0956797619830398>.
- Bae, G. Y., & Luck, S. J. (2020). Serial dependence in vision: Merely encoding the previous-trial target is not enough. *Psychonomic Bulletin and Review*, 27(2), 293–300, <https://doi.org/10.3758/S13423-019-01678-7/FIGURES/3>.
- van Bergen, R. S., & Jehee, J. F. M. (2019). Probabilistic representation in human visual cortex reflects uncertainty in serial decisions. *Journal of Neuroscience*, 39(41), 8164–8176, <https://doi.org/10.1523/JNEUROSCI.3212-18.2019>.
- Bilacchi, C. M., Sirius, E. V. P., Cravo, A. M., & de Azevedo Neto, R. M. (2022). Temporal dynamics of implicit memory underlying serial dependence. *Memory and Cognition*, 50(2), 449–458, <https://doi.org/10.3758/S13421-021-01221-X/TABLES/4>.
- Bliss, D. P., Sun, J. J., & D’Esposito, M. (2017). Serial dependence is absent at the time of perception but increases in visual working memory. *Scientific Reports*, 7(1), 14739, <https://doi.org/10.1038/S41598-017-15199-7>.
- Ceylan, G., Herzog, M. H., & Pascucci, D. (2021a). Serial dependence does not originate from low-level visual processing. *Cognition*, 212, 104709, <https://doi.org/10.1016/j.cognition.2021.104709>.
- Ceylan, G., Herzog, M. H., & Pascucci, D. (2021b). Serial dependence is related to the task and not the stimulus. *Journal of Vision*, 21(9), 2495, <https://doi.org/10.1167/JOV.21.9.2495>.
- Cicchini, G. M., Mikellidou, K., & Burr, D. C. (2018). The functional role of serial dependence. *Proceedings of the Royal Society B*, 285(1890), 20181722, <https://doi.org/10.1098/RSPB.2018.1722>.
- Collins, T. (2019). The perceptual continuity field is retinotopic. *Scientific Reports*, 9(1), 1–6, <https://doi.org/10.1038/s41598-019-55134-6>.
- DeCarlo, L. T., & Cross, D. V. (1990). Sequential effects in magnitude scaling: Models and theory. *Journal of Experimental Psychology: General*, 119(4), 375–396, <https://doi.org/10.1037/0096-3445.119.4.375>.
- Feigin, H., Baror, S., Bar, M., & Zaidel, A. (2021). Perceptual decisions are biased toward relevant prior choices. *Scientific Reports*, 11(1), 1–16, <https://doi.org/10.1038/s41598-020-80128-0>.
- Fischer, C., Czoschke, S., Peters, B., Rahm, B., Kaiser, J., & Bledowski, C. (2020). Context information supports serial dependence of multiple visual objects across memory episodes. *Nature Communications*, 11(1), 1–11, <https://doi.org/10.1038/s41467-020-15874-w>.
- Fischer, J., & Whitney, D. (2014). Serial dependence in visual perception. *Nature Neuroscience*, 17(5), 738–743, <https://doi.org/10.1038/nn.3689>.
- Fornaciai, M., & Park, J. (2018). Attractive serial dependence in the absence of an explicit task. *Psychological Science*, 29(3), 437–446, <https://doi.org/10.1177/0956797617737385>.
- Fornaciai, M., & Park, J. (2019). Spontaneous repulsive adaptation in the absence of attractive serial dependence. *Journal of Vision*, 19(5), 21, <https://doi.org/10.1167/19.5.21>.
- Fritsche, M., & de Lange, F. P. (2019). The role of feature-based attention in visual serial dependence. *Journal of Vision*, 19(13), 21, <https://doi.org/10.1167/19.13.21>.
- Fritsche, M., Mostert, P., & de Lange, F. P. (2017). Opposite effects of recent history on perception and decision. *Current Biology*, 27(4), 590–595, <https://doi.org/10.1016/J.CUB.2017.01.006>.
- Fritsche, M., Spaak, E., & de Lange, F. P. (2020). A Bayesian and efficient observer model explains concurrent attractive and repulsive history biases in visual perception. *ELife*, 9, 1–32, <https://doi.org/10.7554/ELIFE.55389>.
- Fulvio, J. M., & Postle, B. R. (2020). Cognitive control, not time, determines the status of items in working memory. *Journal of Cognition*, 3(1), 1–8, <https://doi.org/10.5334/JOC.98/METRICS/>.
- Glasauer, S., & Shi, Z. (2022). Individual beliefs about temporal continuity explain variation of perceptual biases. *Scientific Reports*, 12(1), 1–15, <https://doi.org/10.1038/s41598-022-14939-8>.
- Kalm, K., & Norris, D. (2018). Visual recency bias is explained by a mixture model of internal representations. *Journal of Vision*, 18(7), 1, <https://doi.org/10.1167/18.7.1>.

- Kanai, R., Knapen, T. H. J., van Ee, R., & Verstraten, F. A. J. (2007). Disruption of implicit perceptual memory by intervening neutral stimuli. *Vision Research*, 47(20), 2675–2683, <https://doi.org/10.1016/J.VISRES.2007.06.016>.
- Kiyonaga, A., Scimeca, J. M., Bliss, D. P., & Whitney, D. (2017). Serial dependence across perception, attention, and memory. *Trends in Cognitive Sciences*, 21(7), 493–497, <https://doi.org/10.1016/J.TICS.2017.04.011>.
- Manassi, M., Ghirardo, C., Canas-Bajo, T., Ren, Z., Prinzmetal, W., & Whitney, D. (2021). Serial dependence in the perceptual judgments of radiologists. *Cognitive Research: Principles and Implications*, 6(1), 65, <https://doi.org/10.1186/S41235-021-00331-Z>.
- Manassi, M., Kristjánsson, Á., & Whitney, D. (2019). Serial dependence in a simulated clinical visual search task. *Scientific Reports*, 9(1), 1–10, <https://doi.org/10.1038/s41598-019-56315-z>.
- Manassi, M., Liberman, A., Kosovicheva, A., Zhang, K., & Whitney, D. (2018). Serial dependence in position occurs at the time of perception. *Psychonomic Bulletin and Review*, 25(6), 2245–2253, <https://doi.org/10.3758/S13423-018-1454-5/FIGURES/4>.
- Murai, Y., & Whitney, D. (2021). Serial dependence revealed in history-dependent perceptual templates. *Current Biology*, 31(14), 3185–3191.e3, <https://doi.org/10.1016/J.CUB.2021.05.006>.
- Pascucci, D., Mancuso, G., Santandrea, E., Libera, C. D., Plomp, G., & Chelazzi, L. (2019). Laws of concatenated perception: Vision goes for novelty, decisions for perseverance. *PLoS Biology*, 17(3), e3000144, <https://doi.org/10.1371/journal.pbio.3000144>.
- Pascucci, D., & Plomp, G. (2021). Serial dependence and representational momentum in single-trial perceptual decisions. *Scientific Reports*, 11(1), 16750, <https://doi.org/10.1038/s41598-021-89432-9>.
- Pascucci, D., Tanrikulu, Ö. D., Ozkirli, A., Houborg, C., Ceylan, G., Zerr, P., . . . Kristjánsson, Á. (2023). Serial dependence in visual perception: A review. *Journal of Vision*, 23(1), 9, <https://doi.org/10.1167/JOV.23.1.9>.
- Rafiei, M., Hansmann-Roth, S., Whitney, D., Kristjánsson, Á., & Chetverikov, A. (2021). Optimizing perception: Attended and ignored stimuli create opposing perceptual biases. *Attention, Perception, and Psychophysics*, 83(3), 1230–1239, <https://doi.org/10.3758/S13414-020-02030-1/FIGURES/5>.
- Samaha, J., Switzky, M., & Postle, B. R. (2019). Confidence boosts serial dependence in orientation estimation. *Journal of Vision*, 19(4), 25, <https://doi.org/10.1167/19.4.25>.
- Shan, J., & Postle, B. R. (2022). The influence of active removal from working memory on serial dependence. *Journal of Cognition*, 5(1), 31, <https://doi.org/10.5334/JOC.222/>.
- Stewart, N., Brown, G. D. A., & Chater, N. (2005). Absolute identification by relative judgment. *Psychological Review*, 112(4), 881–911, <https://doi.org/10.1037/0033-295X.112.4.881>.
- World Medical Association. (2013). World Medical Association declaration of Helsinki: Ethical principles for medical research involving human subjects. *Jama*, 310(20), 2191–2194, <https://doi.org/10.1001/jama.2013.281053>.
- Zhang, H., & Alais, D. (2020). Individual difference in serial dependence results from opposite influences of perceptual choices and motor responses. *Journal of Vision*, 20(8), 2, <https://doi.org/10.1167/JOV.20.8.2>.