Clashing Memories: Interference in Working Memory modulates Serial Dependence

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Abstract

Visual perception reflects a combination of current input, past information, and expectations. Serial dependence describes how prior and present stimuli interact, often resulting in attractive biases toward previously seen inputs, particularly under uncertainty about the incoming stimulus feature. While prior work manipulated noise by manipulating stimulus properties, here we directly altered the quality of internal representations using an intermediate task performed during the retention interval. Participants viewed oriented Gabor patches and reproduced their orientation after a delay. During that delay, they completed one of several intermediate tasks: judging the size of circles (containing no orientation information), the length or orientation of lines, the frequency of tones, or no task (Control condition). These manipulations allowed for a detailed assessment of the role of working memory load and inter-item competition in memory on the precision of the encoded Gabor orientation and subsequently, on the strength of serial dependence. Results showed that any intermediate task which required encoding more stimuli in working memory increased the strength of serial dependence. This bias was present even with an auditory task. Because memory precision often decreases when more items need to be encoded, this reduction in precision can explain why serial dependence increased under higher working memory load. However, sharing the same feature dimension (e.g., orientation) did not further increase serial dependence, though it did increase response variability. These findings offer novel evidence that degraded memory precision, not just stimulus noise, enhances biases towards past input, shaping serial dependence through internal uncertainty. Furthermore, it highlights the interdependence between serial dependence and visual working memory.

Introduction

Visual perception is noisy due to external noise in the environment such as occlusions, eye blinks, or lightness changes and internal neural noise. Hence, the visual system needs to combine different sources of information to make the correct inferences. One obvious source of information is past information since the environment changes only slowly. This results in serial correlations and temporal continuity (Dong & Atick, 1995). The present noisy visual input is likely to be similar to the previous input and therefore, incorporating prior and present information is advantageous. Prior information influences how we perceive the environment, our behavior and how we make decisions (Anstis et al., 1998; Gekas et al., 2019; Kiyonaga et al., 2017; Kristjánsson & Campana, 2010; Manassi et al., 2023; Pascucci et al., 2023)

Work in the field of serial dependence has investigated how this combination of past and present information affects perception and decision making by sequentially presenting visual targets to observers (J. Fischer & Whitney, 2014; see Kiyonaga et al., 2017; Manassi et al., 2023 and Pascucci et al., 2023 for reviews). These studies revealed strong attractive biases towards previously seen stimuli. Serial dependence is thought to stabilize noisy inputs by combining incoming information with prior experience resulting in a change of appearance of the present input. Fischer and Whitney's (2014) findings revealed various aspects of serial dependence, including the influence of feature similarity and spatiotemporal proximity of previously attended stimuli. Specifically, attractive biases are stronger for similar stimuli presented close in time and space. They proposed that serial dependence serves as a fundamental mechanism of maintaining perceptual stability (Liberman et al., 2016) and continuity of representations, termed a continuity field. These attractive biases towards previous information have been found to be a general mechanism of perception and cognition. These biases towards recent input have been found for a variety of visual features such as orientation (Fischer & Whitney, 2014; Fritsche et al., 2017; Houborg et al., 2023; Tanrikulu et al., 2023) and motion direction (Fischer et al., 2020), position (Bliss et al., 2017; Manassi et al., 2018), color (Barbosa & Compte, 2020), shape (Collins, 2022b, 2022a; Manassi et al., 2019), faces (Liberman et al., 2014) and their emotions (Liberman & Whitney, 2015), facial attractiveness (Taubert et al., 2016) but also for ensembles (Manassi et al., 2017), perceived variance (Suárez-Pinilla et al., 2018), oculomotor behaviour (Goettker & Stewart, 2022), when rating artworks (Kim et al., 2019) and numerosity (Fornaciai & Park, 2018b).

Fischer & Whitney (2014) and many of the follow-up studies reported that the strength of these attractive biases depends on the feature similarity between consecutive trials. Strong attractive biases are commonly found when features in a temporal sequence are similar and diminish with large discrepancy between stimuli. Furthermore, very dissimilar, and distant stimuli can even lead to a repulsive bias in a subsequent reproduction task (Fritsche et al., 2017; Fritsche & de Lange, 2019, (Rafiei, Chetverikov, et al., 2021; Rafiei et al., 2023; Rafiei, Hansmann-Roth, et al., 2021). These modulations might stem from the visual system's expectation of such discrepant information as originating from different objects, thereby reducing the tendency to integrate them. For instance, Taubert et al. (2016) found that repulsive biases of facial attributes are more likely for changeable features like expressions, while stable features such as gender led to attractive effects.

If past and present information is integrated to represent the continuity in the visual environment, one might speculate whether performance on such a task is consistent with a Bayesian sensory integration strategy? Serial dependence should be stronger when incoming information is uncertain and weaker if incoming information is certain and precise. Results do suggest that serial dependence scales with the uncertainty in the environment. Cicchini et al. (2018) presented observers with Gabors that had high and low spatial frequencies and Gabors with oblique or cardinal orientations and compared how the strength of serial dependence varies with the uncertainty the stimulus. As predicted, Gabors with low spatial frequencies and Gabors with oblique orientations resulted in larger serial dependence compared to high spatial frequency Gabors and orientations close to the cardinal axes. However, a model of serial dependence based on a Bayesian ideal observer should not just take the uncertainty in the incoming information into account but also the uncertainty in the previous trial. Previous and current input inputs should be optimally weighted by their reliability (Knill, 2007; Körding & Wolpert, 2006). In a study by (van Bergen & Jehee, 2019) observers were presented with Gabors and had to replicate their orientations. The authors used fMRI and a probabilistic decoding analysis to decode cortical uncertainty. Trials were then grouped in different bins depending on whether the decoded cortical uncertainty was higher on the current compared to the previous trial and vice versa. These binned trials were then compared with the behavioural data and results showed that indeed, an attractive bias towards the previous Gabor was stronger when a low uncertainty trial was followed by a high uncertainty trial and serial dependence was smaller when a high uncertainty trial was followed by a low uncertainty trial. While Cicchini et al. (2018) did not take the uncertainty of the previous trial into account, Ceylan et al. (2021) and Gallagher & Benton, (2022) combined low and high uncertainty trials by manipulating the spatial frequency of their Gabor patches. Low spatial frequency is generally associated with high uncertainty: Judging the orientation precisely is harder when a Gabor has low spatial than when having high spatial frequencies. Both studies reported that serial dependence was manipulated by the uncertainty of the current trial, but not following an ideal observer model. Uncertainty from the previous trial was not optimally considered, violating the assumption of an ideal Bayesian observer. However, these results overall show that the reliability in the stimulus plays a profound role in the temporal integration of visual information. Uncertainty about the true orientation also increases when stimuli are presented further in depth and when oriented in depth compared to when oriented along the fronto-parallel plane (Tanrikulu et al., 2023).

While originally studied as a phenomenon of visual perception (Czoschke et al., 2019; J. Fischer & Whitney, 2014; Fornaciai & Park, 2018a; Lau & Maus, 2019; Liberman et al., 2014; Liberman & Whitney, 2015; Manassi et al., 2018; St. John-Saaltink et al., 2016; Xia et al., 2016) accumulating evidence suggests that working memory (WM) plays a central role in mediating these biases. Rather than being purely a product of low-level sensory mechanisms, serial dependence appears to arise, at least in part, from the cognitive processes that support the short-term maintenance and integration of information in working memory (Ceylan et al., 2021; Ceylan & Pascucci, 2023; Cheng, Chen, Glasauer, et al., 2024; Cheng, Chen, Yang, et al., 2024; Cheng et al., 2025; Feigin et al., 2021; C. Fischer et al., 2020; Fritsche et al., 2017; Houborg et al., 2023; Pascucci et al., 2019; Pascucci & Plomp, 2021; Sheehan & Serences, 2022). Working memory acts as a temporary storage system for information that is no longer physically present. In the context of serial dependence, WM serves as the source of past stimulus information that can bias current perception or decision-making. When a stimulus is encoded and held in WM, even briefly, it creates a trace that can persist and exert influence on subsequent stimuli. Interrupting these circuits with e.g., TMS (Transcranial Magnetic Stimulation) directly affects memory representations (Akrami et al., 2018) and the strength of serial dependence (Barbosa et al., 2020; De Azevedo Neto & Bartels, 2021). Behavioural studies by Fritsche et al. (2017) and Bliss et al. (2017) have additionally shown that as the quality of current information decreases over time, there is an increased reliance on past information. Attractive biases also increase with the number of items presented before an estimation is made (Ceylan & Pascucci, 2023; Pascucci et al., 2019; Pascucci & Plomp, 2021). This suggests that serial dependence acts as a compensatory mechanism, enhancing overall precision when current information degrades in working memory. The length of the retention interval between stimulus presentation and the reproduction task modulates the strength of serial dependence indicating that visual working memory contributes to serial dependence. Bliss et al. (2017) showed that serial dependence increases with longer retention intervals, indicating that when working memory representations decay, observer's reproductions are stronger influenced by previous stimuli. Serial dependence is also modulated by the internal states of the observer such as where attention is directed to or how confident an observer is about their current performance. The strength of the attractive bias is directly modulated by attention (Fritsche & De Lange, 2019): When observers attention is directed to an irrelevant feature, serial dependence is weaker than when observers attend to the feature of interest. However, unattended stimuli can also induce attractive biases (Fornaciai & Park, 2018). Observers' confidence about their own performance also influences the strength of serial dependence. Serial dependence is often stronger towards past stimuli when their corresponding response was made with high confidence (Gallagher & Benton, 2023; Samaha et al., 2019; Suárez-Pinilla et al., 2018).

While such a fundamental mechanism of perception and cognition exist, the underlying mechanisms are still under debate. Whether serial dependence originates at the perceptual or at postperceptual stages and hence, the role of working memory in generating this bias towards previous input still remains unclear.

A recent study by Markov et al. (2024) examined the role of visual working memory load on serial dependence. Across two experiments, participants performed a continuous orientation reproduction task using Gabor patches. On some trials, an additional memory load was introduced in the form of an intermediate visual working memory task. This task required participants to remember abstract shapes, and the load was systematically manipulated: in low-load trials, the shapes were identical and easy to maintain, while in high-load trials, participants had to remember multiple distinct shapes. This allowed the authors to examine not only how memory load on the current trial affected serial dependence, but also how load from the previous trial modulated the influence of past information on present perception. The key findings revealed a bidirectional effect of working memory load on serial dependence. First, when the current trial included a high memory load, serial dependence increased: participants' orientation estimates were more strongly biased toward the previous stimulus. This supports the idea that when current visual encoding becomes less precise due to competing cognitive demands, the visual system compensates by leaning more heavily on recent past information. In contrast, when the memory load on the previous trial was high, serial dependence decreased. This suggests that a high working memory load impairs the storage or accessibility of past stimulus representations, thereby reducing their influence on subsequent perception. Notably, these changes in serial dependence occurred independently of overall task performance or precision. That is, the observed modulation of serial dependence could not be fully explained by changes in the variability of responses, reinforcing the idea that working memory load specifically affects how past information is weighted in perceptual decisions rather than simply degrading signal quality. These findings align with theories based on the variable precision model of visual working memory (Bays & Husain, 2008; Fougnie et al., 2012; Ma et al., 2014; Van Den Berg et al., 2012). This model claims that memory resources are not evenly distributed across items or trials; instead, the precision with which an item is encoded fluctuates depending on the cognitive load and attentional allocation. When multiple items must be stored simultaneously, or when an intervening task imposes additional demands, fewer resources are available per item. As a result, the precision of the representation deteriorates, increasing internal uncertainty about the underlying stimulus feature. In this context, the observed increase in serial dependence under high memory load can be interpreted as a compensatory mechanism: when the representation of the current stimulus is imprecise, the visual system leans more heavily on the stimulus from the previous trial to stabilize perception. This weighting of prior information is adaptive under uncertainty, consistent with Bayesian integration frameworks in which noisy or unreliable evidence is supported with expectations or priors. Thus, these findings support the idea that serial dependence is not merely a product of low-level sensory persistence but there is a strong interplay between working memory resources and serial dependence.

Current aims

Uncertainty in visual information has been shown to modulate the strength of serial dependence, with greater uncertainty often leading to a stronger reliance on recent past stimuli. In the present study, we aim to investigate whether this modulation is driven by the reliability of the representation in working memory, rather than by stimulus uncertainty alone. Drawing on the framework of flexible-resource models of working memory, which states that increasing the number of items stored in memory reduces the precision with which each item is maintained (Bays & Husain, 2008; Fougnie et al., 2012; Ma et al., 2014; Van Den Berg et al., 2012) we examine whether information retained from a secondary working memory task interferes with, and alters observers' bias toward prior visual input. Previous work has demonstrated that as more items are stored, memory precision declines, and this degradation is further exacerbated when items are similar, due to increased inter-item interference (Oberauer & Lin, 2017; Wennberg & Serences, 2024). The recent target confusability competition (TCC) model of working memory also demonstrates that with an increasing number of items sensitivity and hence, performance on a memory task decreases and predicts that observers would do more mistakes on a memory task when a foil is similar to the target due to a familiarity signal that is similar for the target and a foil (Schurgin et al., 2020).

Building on this, we designed three experiments to test whether 1) working memory load, and 2) the similarity of information maintained in working memory modulate serial dependence in an orientation reproduction task. In the first experiment, we replicate previous findings (Markov et al., 2024) by introducing an intermediate memory task between stimulus presentation and reproduction. Critically, in Experiment 2 we manipulate the feature similarity between the stimuli in the intermediate task and those in the serial dependence task to assess whether a feature-dimension overlap increases or decreases serial dependence. In a final experiment, we explore the cross-modal effect of an auditory working memory task on visual serial dependence, to determine whether such interference is modality-specific whether it reflects a domain-general cognitive resource competition. Together, these experiments aim to clarify the role of memory precision and feature dimension similarity in shaping how past and current information is integrated into perceptual decisions.

Material & Methods Experiment 1

Procedure/Task

On each trial, observers conducted two types of tasks: An orientation reproduction task where they were asked to reproduce the orientation of a Gabor and an intermediate comparison task, where they had to judge whether two different visual stimuli were identical or not. Each trial consisted of two adjustment tasks and the comparison task. The comparison task was performed during the retention period between the presentation of the second Gabor and the adjustment response. Hence, it functioned as an intermediate task to modulate the strength of serial dependence. Observers did three different intermediate task conditions in three different sessions. These conditions were blocked and counterbalanced across observers.

Each trial (Figure 1) started with a white fixation cross, presented for 500ms. Then the first Gabor appeared for 500ms, followed by a mask for 500ms. Observers were asked to remember and replicate the orientation of the first Gabor in a subsequent adjustment task. A response circle appeared at the same location as the Gabor. The response circle was a black circle with two black dots that marked the extremities of an imaginary line. This response circle reduces the influence of additional physical orientation signals. The initial orientation of the response circle was randomly set at the beginning of the trial. After observers finished their adjustment response, a second Gabor appeared for 500ms followed by another mask for 500ms. Observers were again instructed to remember the orientation of the second Gabor. Before the response circle appeared, the intermediate task had to be conducted. This task remained constant throughout a single session. On the intermediate task (Figure 2) observers either compared the size of two circles, or, in the Control condition, observers simply had to wait until the response circle appeared. The circles appeared for 500ms in succession with a 500ms blank in between. Observers reported whether the circles had the same or a different size by pressing the s- or d-key respectively. After submitting their responses and an additional blank for 500ms, the response circle appeared, and observers were instructed to replicate the orientation of the second Gabor. After submitting their responses, the next trial started. In the control condition, the response circle appeared after 2.75s to match the approximate time to conduct the intermediate task in the other two conditions (2s of stimulus presentation and blanks, and an average response time of approximately 750ms). The response circles remained on the screen until a response was made, and approved, by pressing the space bar.

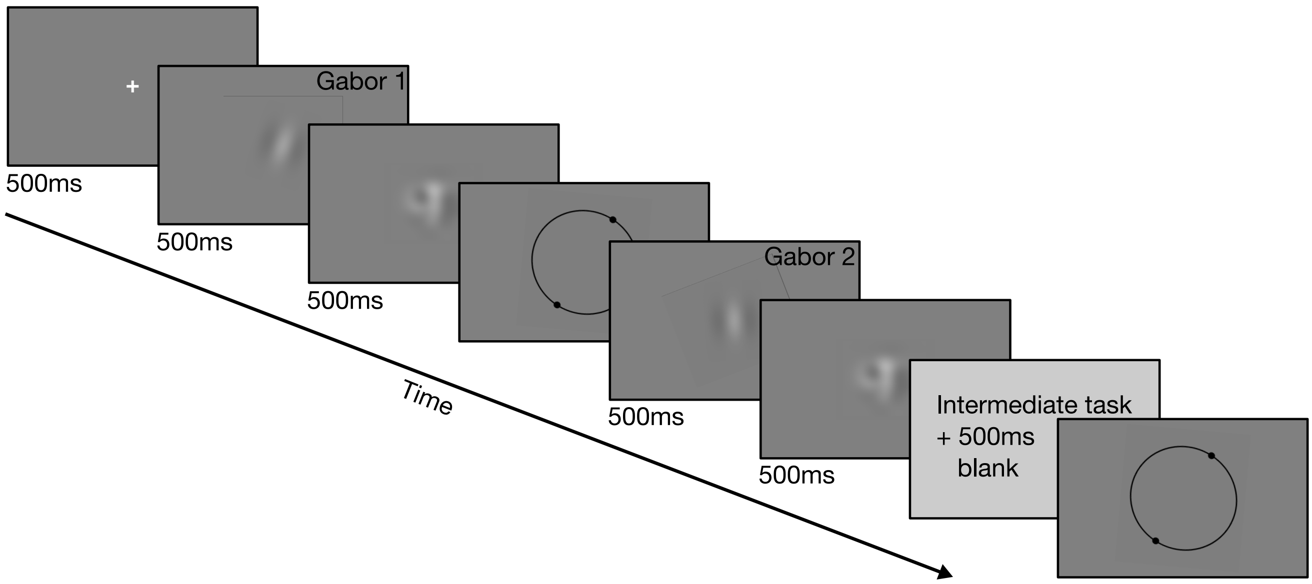

Figure 1: Overview of a single trial. Each trial started with a fixation cross, followed by an inducer Gabor and a mask. A response circle appeared that observers could rotate to match to the orientation of the inducer Gabor patch. After the response the second Gabor appeared. Before the presentation of a second response circle, the intermediate task occurred. After the intermediate task, the second response circle occurred until observers finished their adjustment response.

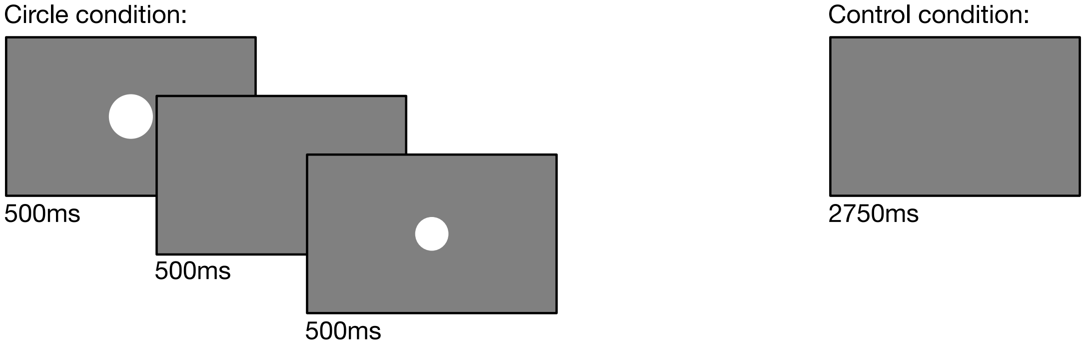

Figure 2: Overview of the two different conditions. In the circle condition, two circles were presented in sucession with a 500ms blank in between. In the control condition, observers were presented with a blank screen for 2750ms.

Stimuli

Gabor patches were 2° × 2° Gaussian-windowed sinusoidal grating with a Michelson contrast of 25% and a spatial frequency of 1 cycle/degree. The orientation of the first Gabor was randomly selected at the beginning of the trial covering the entire orientation range between 0 and 179°, in steps of 1°. The orientation of the second Gabor was either -10 or +10°away from the first Gabor. This distance was based on previous serial dependence studies showing that feature similarity modulates serial dependence. Attractive serial dependence is largest when consecutive stimuli are similar. In the circle condition stimuli on the intermediate task consisted of two white circles presented in succession. One circle had a fixed size of 2°diameter and the other circle size was either 1.6, 1.8, 2, 2.2, or 2.4° in diameter. The order of presentation was counterbalanced across trials.

Apparatus

All stimuli were displayed on a 24-inch LCD monitor (ASUS, VX248h). The resolution was set to 1920 × 1080. All stimuli were displayed using PsychoPy 2022.2.4 that ran on a Desktop PC with Windows 10 at 60 Hz. A subset of 8 participants was tested on a MacBook Pro (60Hz) connected to the same 24-inch LCD monitor, due to a temporary malfunctioning of the testing computer during the testing period.

Observers

24 observers participated in Experiment 1. All observers completed the two conditions in two distinct sessions on different days. Both sessions were counterbalanced across observers. All observers (except for one author) were naïve to the purpose of the study and all had normal or corrected-to-normal vision. They all gave written, informed consent. All experiments were approved by the ethics committee of the National Bioethics committee in Iceland (Vísindasiðanefnd, http://vsn.is) and performed in accordance with their requirements and guidelines and the Declaration of Helsinki. Observers received a gift card after completing all sessions for a local mall in Reykjavík, Iceland.

Data analysis

First, adjustment errors were calculated as the difference between the Gabor orientation and the orientation indicated by the observer bounded to +/-90 degrees. The average adjustment error and the average variability of the adjustment error were calculated using circular statistics with the *circular* package in R.

In the main analysis we compared the strength of serial dependence by comparing the attraction of the second Gabor to the first Gabor between the three conditions. The average adjustment error was calculated separately for the counterclockwise and clockwise relationship between the first and the second Gabor. We calculate the weight of the past stimuli by the slope of a linear regression to the two data points. A steeper slope indicates a larger bias between the first and the second Gabor. A positive slope indicates an attractive bias of the second Gabor towards the first Gabor, a negative slope indicates a repulsion from the first Gabor and a slope at around 0 indicates no bias towards or away from the first Gabor (Cicchini et al., 2018). To assess the influence of the intermediate task on the strength of serial dependence, the steepness of the slope for each observer was compared across conditions. Trials in which the adjustment error is larger than three standard deviations from observers' average errors or the adjustment time was larger than 10s were excluded from the analysis, following exclusion criteria regularly applied to data examining serial dependence with an adjustment task (Ceylan et al., 2021; Houborg et al., 2023; Pascucci et al., 2023).

We conducted repeated-measures ANOVAs, with Greenhouse–Geisser corrections, where applicable, after testing for sphericity using Mauchly tests. ANOVAs were conducted in the open-source software R (R Development Core Team, 2012) with the *ez* package (Lawrence, 2016). In addition, the evidence in favor of the alternative hypothesis H1 versus the null hypothesis H0 was assessed using Bayes Factor analyses with the *BayesFactor* package in R.

Results

Each observer participated in two sessions, reproducing the orientation of a previously seen Gabor. To assess whether serial dependence is modulated by an additional working memory task in the retention period between the second Gabor and its orientation reproduction, the strength of serial dependence was compared across conditions.

To assess the strength of serial dependence between the two conditions, the average adjustment errors were plotted separately for the clockwise and counterclockwise relationship between the first and the second Gabor. Attractive serial dependence leads to a positive adjustment error when the orientation of the first Gabor is clockwise from the second Gabor and to a negative adjustment error when the orientation of the first Gabor is counterclockwise from the second Gabor. Figure 3A and B plot the slope for the Control and the Circle condition. The positive slope in all both conditions indicates a bias towards the previous stimuli. Figure 3C summarizes the results and shows the average slopes across both conditions. A paired t-test confirmed that the average slopes were steeper, indicating stronger serial dependence, in the Circle condition when a memory task was conducted while holding the orientation of the Gabor in memory: $t(23)=4.8$, $p<0.001$ and the Bayes Factor[1] ($BF_{10} = 292.1$)

[1] Bayes Factors comprised between 1 and 3 yield anecdotal evidence for H1, values between 3 and 10 yield moderate evidence for H1, values between 10 and 30 bring strong evidence for H1, values between 30 and 100 yield very strong evidence for H1, and values above 100 yield extreme evidence for H1. In the same manner, Bayes Factors comprised between 0.33 and 1 yield anecdotal evidence for H0, values between 0.1 and 0.33 yield moderate evidence for H0, values between 0.033 and 0.1 yield strong evidence for H0, values between

comprised extreme evidence for the alternative hypothesis. Serial dependence was stronger when a memory task was introduced into the retention interval between the presentation and the orientation reproduction of the Gabor. Additionally, we also examined whether observers' adjustment errors became larger when an additional task was introduced. Figure 3D plots the average variability of the adjustment responses separately for each condition. While serial dependence increased when the memory task was introduced, it did not significantly affect the variability of the responses: $t(23)=1.69$, $p>0.05$ and the Bayes Factor ($BF_{10} = 0.74$) provides anecdotal evidence for the Null hypothesis. Serial dependence was stronger when a memory task was introduced into the retention interval between the presentation and the orientation reproduction of the Gabor, but this task did not affect the variability of the adjustment responses.

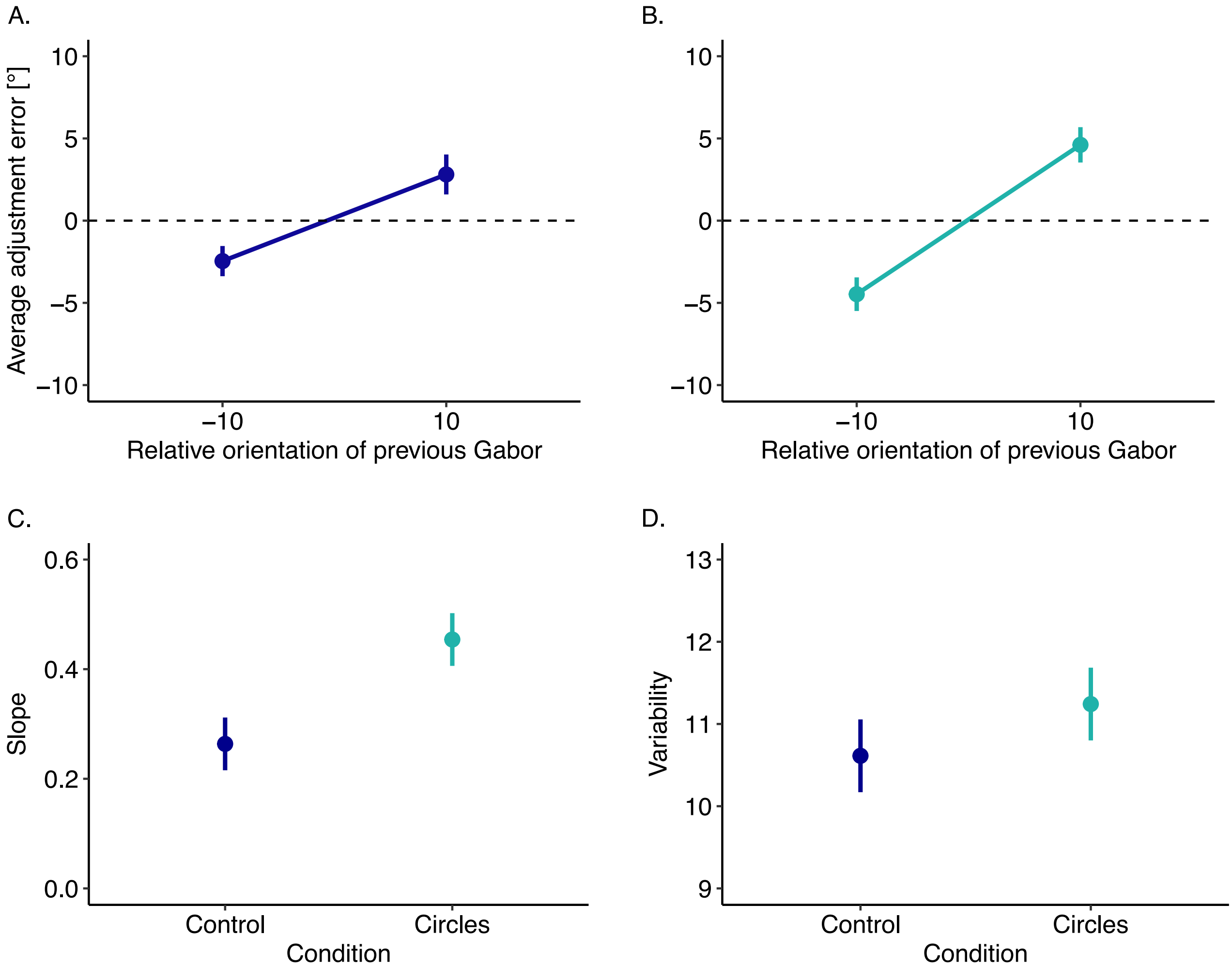

Figure 3: Serial dependence in Experiment 1. Average adjustment errors as a function of the relative orientation between the previous and the current Gabor in the Control condition (A)) and in the Circle condition (B). A positive slope indicates an attractive bias towards the previous stimulus. C. Average slopes extracted from each observer as a function of the three conditions. D. Average variability as function of the three different conditions. Error bars correspond to the confidence intervals adjusted for within-subject variability (Morey, 2008).

0.01 and 0.033 yield very strong evidence for H0, and values below 0.01 yield extreme evidence for H0 (criteria proposed by Jeffreys, 1961, and modified by Lee & Wagenmakers, 2014).

While the presence of an intermediate task increased the strength of serial dependence, we then decided to examine whether the performance on the intermediate task correlated with serial dependence. Figure 4 shows the relationship between performance (average accuracy and average reaction time) and the strength of serial dependence for each observer. The correlation between average accuracy on the intermediate task and serial dependence was not significant, r(22) = 0.48, $p > 0.05$. The correlation between average response time on the intermediate task and the strength of serial dependence was weak but significant, r(22) = 2.23, $p = 0.03$ showing that observers who took longer to reply on the intermediate task also showed slightly stronger serial dependence.

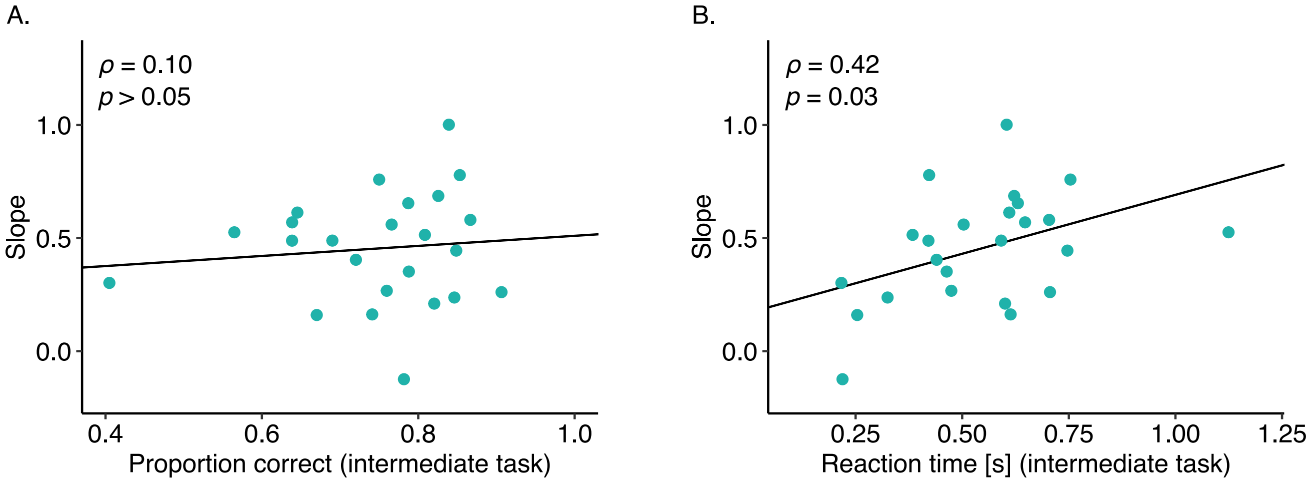

Figure 4: The relationship between the strength of serial dependence and the performance on the intermediate task. A) Correlation between the proportion of correct responses on the intermediate task and the strength of serial dependence. B) Correlation between the average response times on the intermediate task and the strength of serial dependence. Each data point corresponds to a single observer. Note: Response time is measured from the offset of the stimulus, meaning observers could already prepare while the stimulus was on screen.

Discussion Experiment 1

In Experiment 1, we investigated how performing an intermediate memory task influences the strength of serial dependence. Specifically, we compared a control condition—with no intermediate task—to a condition in which participants completed a size-comparison task involving two circles. Importantly, these circles contained no orientation information that could interfere with the memorized orientation of the Gabor stimulus.

The results revealed a clear interaction between working memory content and serial dependence in the orientation reproduction task. Although the inclusion of the intermediate task led to a marked increase in serial dependence (reflected as a stronger bias), it did not significantly affect the variability of reproduction errors. This is noteworthy, given that increased memory load is typically associated with reduced precision. Consistent with the serial dependence literature, our findings suggest that when current representations become less precise (i.e., noisier), the visual system compensates by placing greater reliance on prior information, thereby amplifying serial biases.

While the results from Experiment 1 corroborated the recent findings by (Markov et al., 2024), we extended our investigation by further examining the influence of the intermediate task on serial dependence, with a focus on potential interactions between the memorized Gabor orientation and the features of the stimuli presented during the intermediate task. To this end, we manipulated the feature dimension of the comparison stimuli and their similarity to the orientation feature of the Gabor reproduction task. Participants completed one of three types of intermediate tasks: (1) comparing the size of circles, which contained no orientation information; (2) judging the length of differently oriented lines, which contained orientation information but that was irrelevant to the task; or (3) comparing the orientation of two lines, which directly matched the feature dimension of the Gabor stimulus. This design allowed us to assess how both task-relevant and task-irrelevant feature similarity between concurrently held items influences serial dependence.

Material & Methods Experiment 2

Procedure/Task

The general procedure (Figure 1) was identical to the procedure of Experiment 2. However, the type of intermediate task differed across three different conditions. On the intermediate task, two stimuli were presented in succession for 500ms each separated by a 500ms blank. Observers were asked to compare the two stimuli and judge whether they had identical size/length or orientation.

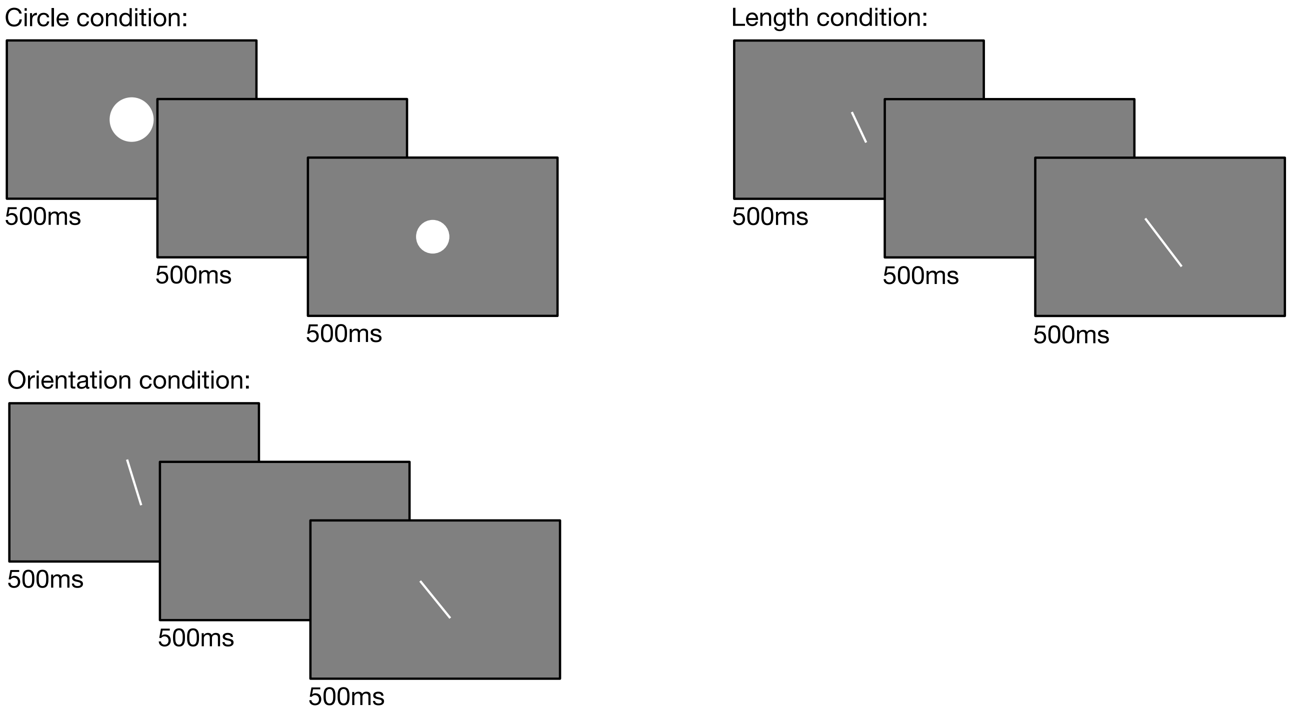

Figure 5: Overview of the three conditions in Experiment 2. Experiment 2 used three different conditions. These conditions referred to the type on intermediate task used in the retention interval. In the Circle condition, two circles were presented, and observers judged whether both circles had the same or different sizes. In the Length condition, observers judged whether two lines had the same length or not. In the Orientation condition, observers judged whether two lines had the same orientation or not. All stimuli were presented in succession for 500ms each separated by a 500ms blank.

Stimuli

All parameters of the Gabor patches were identical to Experiment 1. In the Circle condition stimuli on the intermediate task consisted of two white circles presented in succession. One circle had a fixed size of 2°diameter and the other circle size was either 1.6, 1.8, 2, 2.2, or 2.4° in diameter. The order of presentation was counterbalanced across trials. In the Orientation condition two white lines were presented in succession. Both lines were 2° in length and the orientation of one line was fixed at -70 or 70° away from the first Gabor patch (and consequently +/- 60° or +/- 80° away from the second Gabor). The orientation of the other line was either 0°, 7° or 14°clockwise or counterclockwise from the first line. The order of presentation was counterbalanced across trials. In the Length condition, one line had a fixed length of 2° and the length of the other line was either identical, 0.1°or 0.3° longer or smaller than the fixed line. The order of lines was counterbalanced across trials. The orientation difference of the lines in the Length and in the Orientation condition and the Gabors were selected to ensure that orientations were dissimilar enough from the Gabors. The large distance between the Gabors and the lines on the intermediate tasks was selected to avoid serial dependence between the Gabors and the stimuli from the intermediate task. Large feature similarities do not induce attractive serial dependence.

Apparatus

All stimuli were displayed on a 24-inch LCD monitor (ASUS, VX248h). The resolution was set to 1920 × 1080. All stimuli were displayed using PsychoPy 2022.2.4 that ran on a Desktop PC with Windows 10 at 60 Hz.

Observers

24 observers participated in Experiment 2. Observers completed the three conditions in three distinct sessions on different days. The order was counterbalanced across observers. All observers (except for one author) were naïve to the purpose of the study and all had normal or corrected-to-normal vision. They all gave written, informed consent. All experiments were done in agreement with the local ethics committee from the University of Iceland and the Declaration of Helsinki. Observers received a gift card after completing all sessions for a local mall in Reykjavík, Iceland.

Data analysis

The data analysis and criteria for trial exclusion was identical to Experiment 1.

Results

Each observer participated in three sessions, reproducing the orientation of a previously seen Gabor. In addition, in all conditions they performed a different type of intermediate comparison task. To assess whether serial dependence is modulated by the type of working memory task in the retention period, the strength of serial dependence was compared across conditions.

To assess serial dependence the average adjustment errors were plotted separately for the clockwise and counter-clockwise relationship between the first and the second Gabor. Attractive serial dependence leads to a positive adjustment error when the orientation of the first Gabor is clockwise from the second Gabor and to a negative adjustment error. Figure 5A, B and C plot the slope for the Circle, Length and Orientation condition.

The positive slope in all conditions indicates a bias towards the previous stimuli. Figure 5D summarizes the results and shows the average slopes across all three conditions. A one-factor repeated-measures ANOVA confirmed that there was no difference in the strength of serial dependence across conditions $F(1.4,32.2)=0.1$, $p>0.05$ and the Bayes Factor ($BF_{10} = 0.13$) comprised moderate evidence for the Null hypothesis of no difference across conditions. We observed serial dependence across all conditions, but the type of intermediate task did not further modulate the strength of serial dependence.

Additionally, we examined whether observers' adjustment errors varied depending on the type of intermediate task. Figure 5E plots the average variability of the adjustment responses separately for each condition. While the strength of serial dependence remained stable across all three intermediate tasks, the task did indeed affect the variability of the responses: $F(1.54,35.42)=5.63$, $p<0.01$ and the Bayes Factor ($BF_{10} = 8.2$) provides moderate evidence for the alternative hypothesis. As visible from Figure 5E there was more variability in the adjustment responses when the intermediate task consisted of judging the length or orientation of lines, hence objects that contained orientation information.

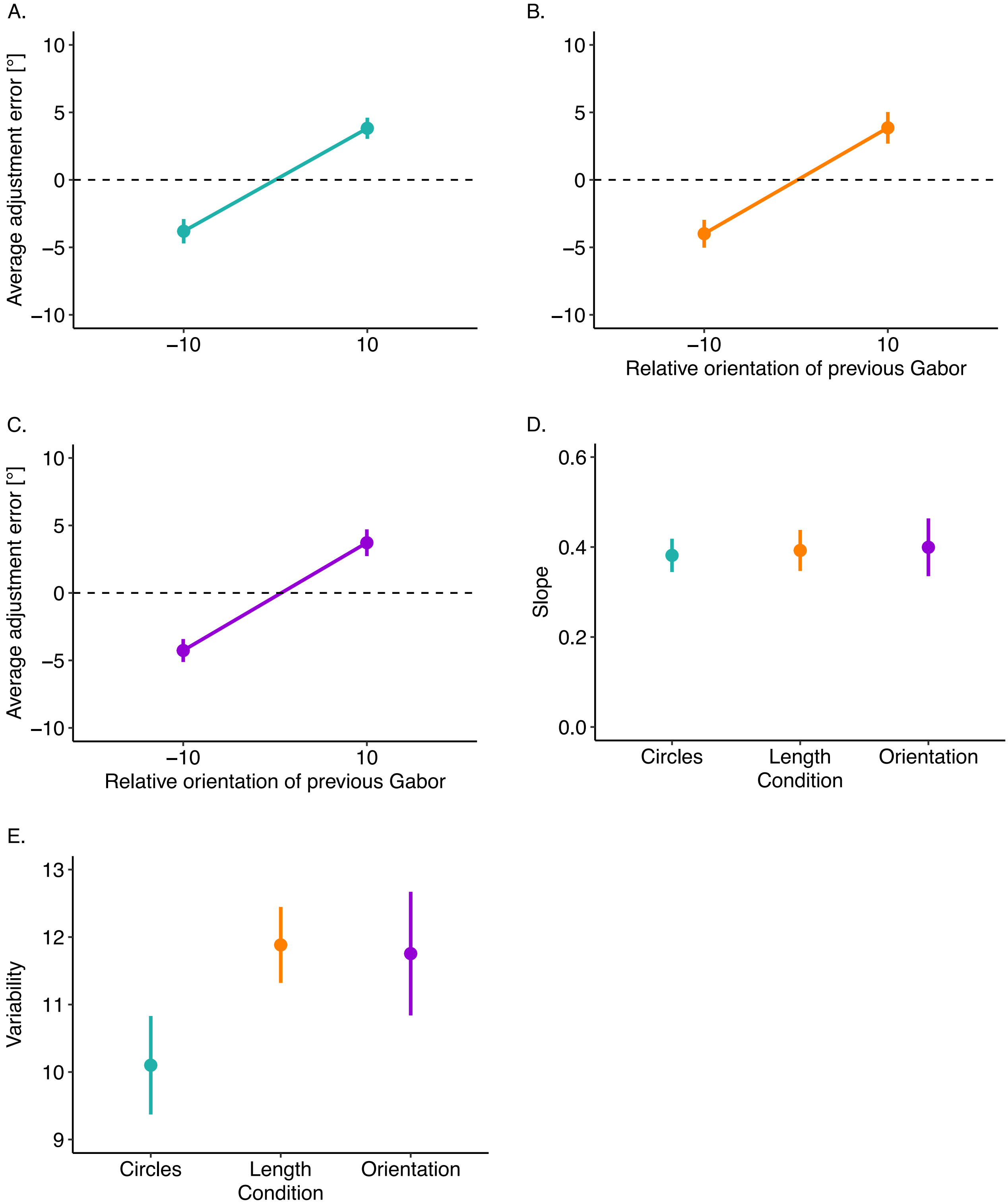

Figure 6: Serial dependence in Experiment 2. A. Average adjustment errors as a function of the relative orientation between the previous and the current Gabor in the Circle condition. B. Average adjustment errors as a function of the relative orientation between the previous and the current Gabor in the Length condition. C. Average adjustment errors as a function of the relative orientation between the previous and the current Gabor in the Orientation condition. A positive slope indicates an attractive bias towards the previous stimulus. D. Average slopes extracted from each observer as a function of the three conditions. E. Average variability as function of the three different conditions. Error bars correspond to the confidence intervals adjusted for within-subject variability (Morey, 2008).

While the mere presence of an intermediate task increased the strength of serial dependence we then examined whether the performance of an observer on the intermediate task correlated with their strength of serial dependence. Figure 7 shows the correlation between the strength of serial dependence and the average performance (accuracy and reaction time) for each condition separately. For both performance measures and for all conditions we found no correlation between performance and serial dependence (all $p > 0.05$).

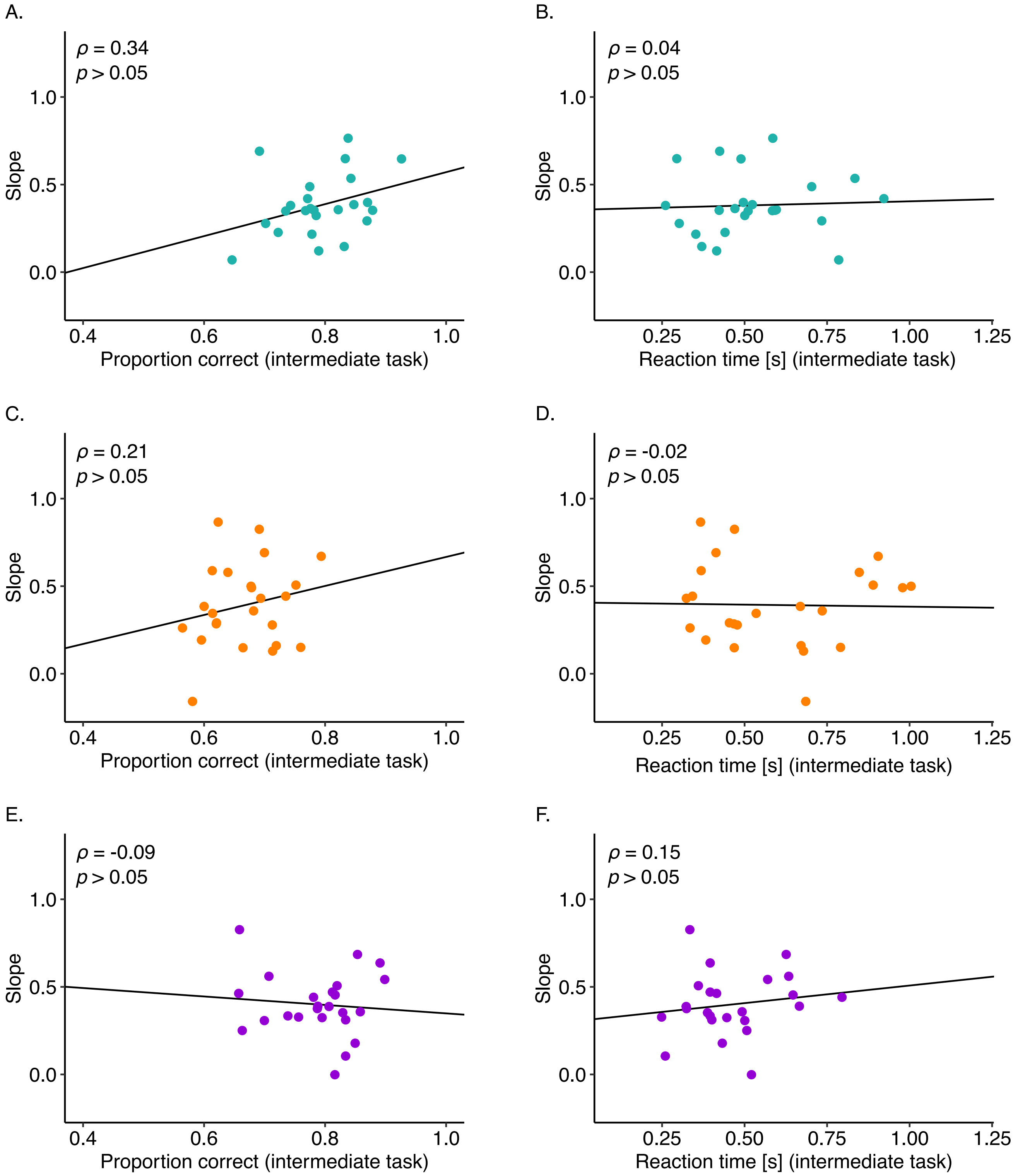

Figure 7: The relationship between the strength of serial dependence and the performance on the intermediate task. A) Correlation between the proportion of correct responses on the intermediate task and the strength of serial dependence in the Circle condition. B) Correlation between the average response times on the intermediate task and the strength of serial dependence in the Circle condition. C) Correlation between the proportion of correct responses on the intermediate task and the strength of serial dependence in the Length condition. D) Correlation between the average response times on the intermediate task and the strength of serial dependence in the Length condition. E) Correlation between the proportion of correct responses on the intermediate task and the strength of serial dependence in the Orientation condition. F) Correlation between the average response times on the intermediate task and the strength of serial dependence in the Orientation condition. Each data point corresponds to a single observer. Note: Response time is measured from the offset of the stimulus, meaning observers could already prepare while the stimulus was on screen.

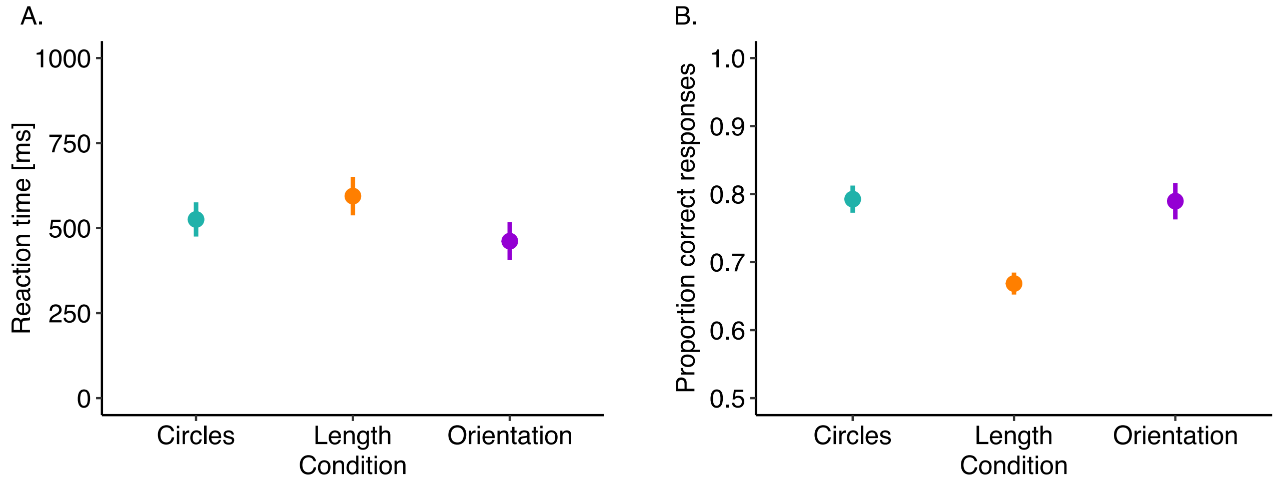

Figure 8: Overview of the performance on the intermediate task. A) Average reaction times across all three conditions. B) Average proportion of correct responses on the intermediate task. Results are averaged across all three difficulty levels and across all observers. Error bars correspond to the confidence intervals adjusted for within-subject variability (Morey, 2008).

While Figure 6E shows that response variability differs, we additionally analyzed whether performance differences are also visible on the intermediate task whether these would follow the same pattern as the performance differences on the adjustment task. Figure 8 shows the average reaction time and proportion of correct responses on the intermediate trial for each condition separately. While the Length and the Orientation condition proved to induce larger variability on the adjustment task, performance on the Length and Orientation intermediate task was not worse than observers' performance on the Circle intermediate task. Response times in the Orientation condition were significantly faster than the response times in the Length condition ($t(23) = 2.9$, $p < 0.01$, $BF_{10}= 4.4$) but not significantly different from the Circle condition ($p > 0.05$, $BF_{10}= 0.62$). Furthermore, we also found no difference in response times between the Circle and Length condition ($p > 0.05$, $BF_{10}= 0.69$, all Bonferroni-corrected). Figure 8B shows the difference in proportion correct for the three different types of intermediate task. Overall, the performance was significantly worse in the Length condition compared to the Circle and Orientation condition ($p < 0.001$, $BF_{10}>100$), but there was no significant difference in performance between the Circle and Orientation condition ($p > 0.05$, $BF_{10}= 0.22$). The difference in variability when the stimulus on the intermediate task contained information orientation was not caused by a general increase in task difficulty on the intermediate task.

Discussion Experiment 2

Experiment 2 examined whether the increase in the strength of serial dependence observed in Experiment 1 was further modulated by the type of stimuli used on the intermediate task. Observers were consistently required to remember the orientation of a Gabor while comparing two different stimuli on the intermediate task. Participants completed one of three types of intermediate tasks: (1) comparing the size of circles, which contained no orientation information; (2) judging the length of differently oriented lines, which contained orientation information but that was irrelevant to the task; or (3) comparing the orientation of two lines, which directly matched the feature dimension of the Gabor stimulus. All three conditions showed clear serial dependence, with slopes comparable to those observed in the Circle condition of Experiment 1. However, there was no evidence that the type of intermediate task modulated the strength of serial dependence. The similarity between the task-relevant feature dimension in the intermediate task and the feature dimension of the reproduction task appeared to be irrelevant. We did, however, observe a slight increase in the variability of adjustment errors for the second Gabor following intermediate tasks that involved objects containing orientation information. The presence of interfering orientation information impaired observers' precision in reproducing the Gabor's orientation. Notably, it did not matter whether orientation was relevant to the intermediate task—the mere presence of orientation content was sufficient to degrade reproduction performance. Hence, we found an increase in variability both for the Length and the Orientation condition.

In Experiment 3, we conducted an additional test to examine the role of working memory load on serial dependence. Specifically, we aimed to determine whether an *auditory* intermediate task could influence *visual* serial dependence. In the Auditory condition, observers listened to two tones presented in succession and judged whether the tones were identical in pitch or not.

Material & Methods Experiment 3

We used two conditions in two separate sessions. The Control condition contained no intermediate task (identical to the Control condition in Experiment 1), and the Auditory condition contained an auditory intermediate task, where observers listened to two tones in succession and judged whether the pitch was the same or not.

Procedure/Task

The general procedure was identical to the procedure of Experiment 1 and 2. However, the type of one intermediate task differed. Observers compared the frequency of two tones before reporting the

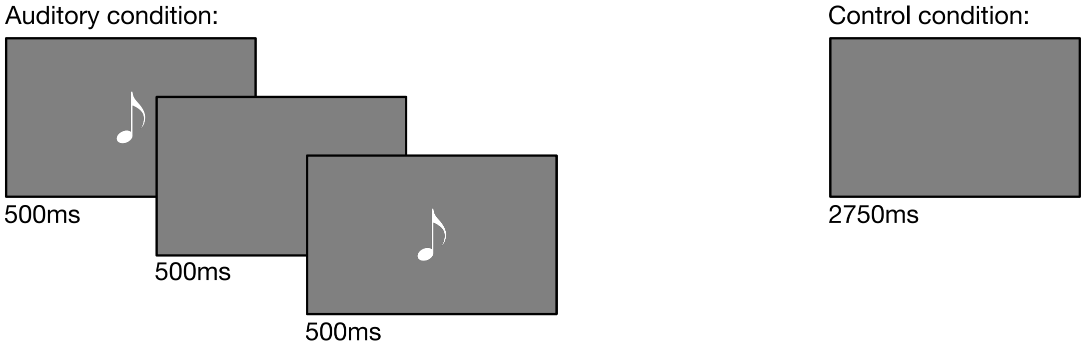

Figure 9: Overview of the three conditions in Experiment 3. The experiment consisted of two conditions. The control condition, identical to the control condition in Experiment 1. In the Auditory condition, two tones were presented in succession for 500ms with a 500ms break in between.

Stimuli

All parameters of the Gabor patches were identical to Experiment 1. In the Auditory condition, observers were presented with two pure tones in succession. One tone had a fixed frequency of 1000 Hz and the other tone had either a 5 or 10 Hz higher or lower frequency. Each tone was presented for 500ms with a 500ms blank in between. Tones were created using the software Audacity Tone Generator. To prevent click sounds when generating a pure tone, especially at the start and end of the tone, we applied a 50ms ramp (fade-in and fade-out) to the amplitude of the signal. Both tones were presented to all observers at ~40dB.

Apparatus

All stimuli were displayed on a 24-inch LCD monitor (ASUS, VX248h). The resolution was set to 1920 × 1080. All stimuli were displayed using PsychoPy 2022.2.4 that ran on a Desktop PC with Windows 10 at 60 Hz. Tones were provided to observers using the Bose Quiet Comfort 35 II headphones.

Observers

24 observers participated in Experiment 3. Observers completed the two conditions in two distinct sessions on different days. Conditions were counterbalanced across observers. All observers (except for two authors) were naïve to the purpose of the study and all had normal or corrected-to-normal vision. They all gave written, informed consent. All experiments were done in agreement with the local ethics committee from the University of Iceland and the Declaration of Helsinki. Observers received a gift card after completing all sessions for a local mall in Reykjavík, Iceland.

Data analysis

The data analysis and criteria for trial exclusion was identical to Experiment 1 and Experiment 2.

Results

Each observer participated in two sessions, reproducing the orientation of a previously seen Gabor. To assess whether serial dependence is also modulated by an additional auditory working memory task in the retention period between the second Gabor and its orientation reproduction, the strength of serial dependence was compared across the Control and the Auditory condition.

To assess the strength of serial dependence between the Control and the Auditory conditions, the average adjustment errors were plotted separately for the clockwise and counter-clockwise relationship between the first and the second Gabor. Attractive serial dependence leads to a positive adjustment error when the orientation of the first Gabor is clockwise from the second Gabor and to a negative adjustment error when the orientation of the first Gabor is counter-clockwise from the second Gabor. Figure 10A and B plot the slope for the Control and the Auditory condition. The positive slope in all both conditions indicates a bias towards the previous stimuli. Figure 10C summarizes the results and shows the average slopes across both conditions. A paired t-test confirmed that the average slopes were steeper, indicating stronger serial dependence, in the Auditory condition when the interreference memory task was conducted while holding the orientation of the Gabor in memory: $t(23)=2.87$, $p=0.009$ and the Bayes Factor ($BF_{10} = 5.5$) comprised moderate evidence for the alternative hypothesis. Serial dependence was stronger when the auditory interference task was introduced into the retention interval between the presentation and the orientation reproduction of the Gabor. There is some evidence that even an auditory task can influence visual serial dependence.

Additionally, we also examined whether observers' adjustment errors became larger when the intermediate task was introduced. Figure 10D plots the average variability of the adjustment responses separately for the Auditory and the Control condition. While serial dependence increased when the intermediate task was introduced, it did not significantly affect the variability of the responses: $t(23)=1.61$, $p>0.05$ and the Bayes Factor ($BF_{10} = 0.67$) provides anecdotal evidence for the Null hypothesis. Serial dependence was stronger when a memory task was introduced into the retention interval between the presentation and the orientation reproduction of the Gabor, but this task did not affect the variability of the adjustment responses.

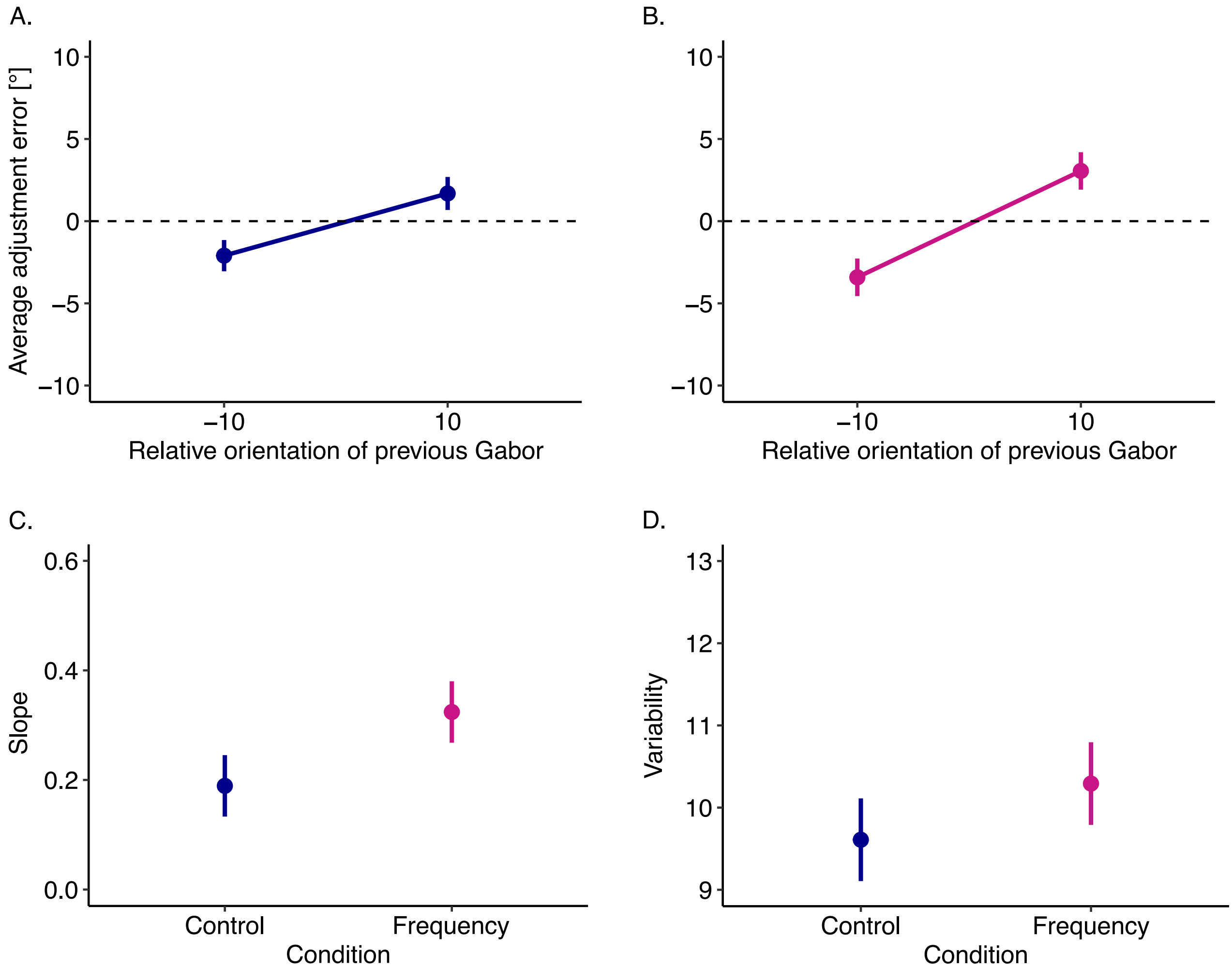

Figure 10: Strength of serial dependence in Experiment 3. Average adjustment errors as a function of the relative orientation between the previous and the current Gabor in the Control condition (A) and in the Auditory condition (B). A positive slope indicates an attractive bias towards the previous stimulus. C. Average slopes extracted from each observer as a function of the two conditions. D. Average variability as function of the two different conditions. Error bars correspond to the confidence intervals adjusted for within-subject variability (Morey, 2008).

As for the previous experiments we additionally examined whether the performance of an observer on the intermediate task correlated with their strength of serial dependence. Figure 11 shows the correlation between the strength of serial dependence and the average performance (accuracy and reaction time) for the control and the Frequency condition separately. Both performance measures did not correlate with the strength of serial dependence.

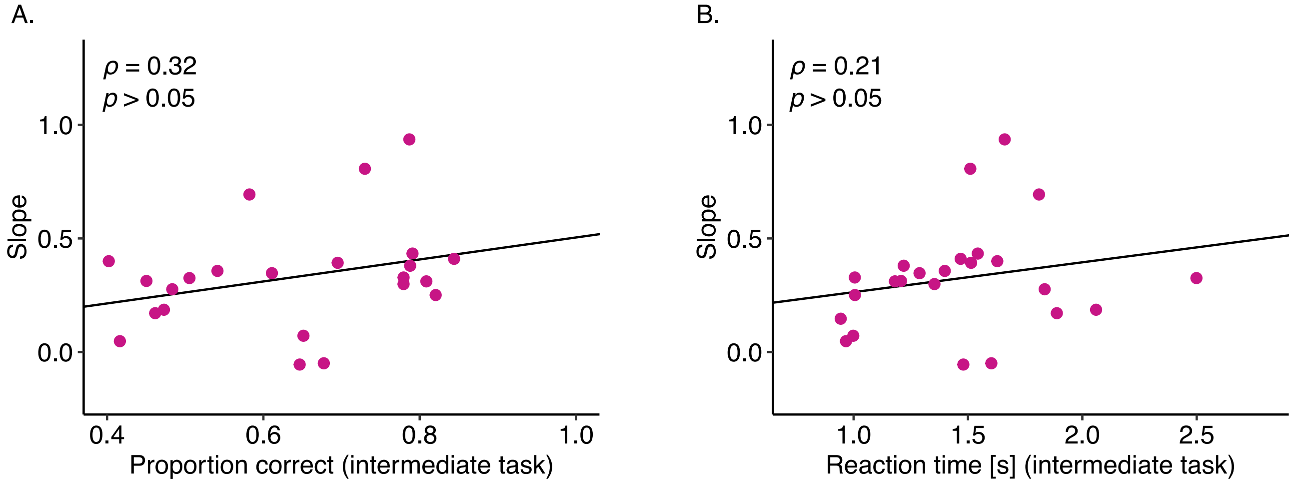

Figure 11: The relationship between the strength of serial dependence and the performance on the intermediate task. A) Correlation between the proportion of correct responses on the intermediate task and the strength of serial dependence in the Frequency condition. B) Correlation between the average response times on the intermediate task and the strength of serial dependence in the Frequency condition. Each data point corresponds to a single observer. Note: Response time is measured from the offset of the stimulus, meaning observers could already prepare while the stimulus was on screen.

Discussion Experiment 3

Experiment 3 provided evidence that even an auditory working memory task can influence the strength of visual serial dependence. As the results from Experiment 1 showed, the intermediate task affects the strength of serial dependence but does not affect the variability of the adjustment responses. In both experiments, the stimulus on the intermediate task contained no orientation information which appears to mainly affect the variability of the adjustment responses. As visible directly from Figure 10C and from the Bayes Factor the effect that the auditory task has on serial dependence appears weaker than the influence induced by a visual intermediate task.

General Discussion

In the current study we examined the role of working memory load and inter-item similarity on the strength of serial dependence. In three distinct experiments we showed that serial dependence increases when a working memory task is introduced into the retention interval between the stimulus and the appearance of the response tool. We found no difference in the strength of serial dependence across different types of intermediate tasks, provided that the memory load (i.e., number of items) was held constant. In other words, whether the feature judged in the intermediate task was the same as or different from the feature assessed in the adjustment task did not affect serial dependence. However, our data revealed that the variability of observers' adjustment responses increased when the intermediate task stimulus also contained orientation information. In the last experiment we showed that an auditory intermediate task can also affect visual serial dependence.

Several studies have shown that working memory load, induced by an increased number of items, leads to a reduction in the precision of stored representations (e.g., Bays & Husain, 2008; Ma et al., 2014; Oberauer & Lin, 2017). While most previous work on serial dependence has focused primarily on manipulating the physical properties of the stimulus itself (e.g., contrast, spatial frequency) to examine how stimulus quality affects serial dependence, fewer studies have directly tested how manipulating the quality of the internal stimulus representation in memory, independent of sensory input, impacts serial dependence (Bae & Luck, 2020; Bansal et al., 2023; Barbosa et al., 2020; Cheng, Chen, Glasauer, et al., 2024; Czoschke et al., 2019; C. Fischer et al., 2020; Gold et al., 2025; Houborg et al., 2023; Markov et al., 2024). Additionally, some previous work showed that observer's internal states and their confidence affects serial dependence again highlighting the involvement of higher cognitive areas (Cheng et al., 2025; Gallagher & Benton, 2023; Ozkirli & Pascucci, 2023; Samaha et al., 2019). Our study contributes to this latter line of research by further emphasizing the role of higher-level cognitive processes in modulating serial dependence. In our study, working memory load increased when observers had to remember not just the Gabor orientation, but also the size, length, orientation or frequency of the two stimuli from the intermediate task. This increased memory load resulted in an increase in serial dependence due to a potentially decreased fidelity of current memory. The intermediate task added in between the stimulus and the response tool must have deteriorated the memory trace and subsequently impacted the strength of serial dependence. Recent drift-diffusion models of VWM propose that as a memory representation weakens due to longer retention intervals or greater load (Panichello et al., 2019). Their results showed that memory representations drift toward stable neural states, or local attractors to counteract the introduced noise by the retention interval or load. They obtained not just an increase in diffusive noise but also an increase in the strength of the drift towards the attractors. These attractors might correspond to representations of recently experienced stimuli. Adding the intermediate task into the retention interval increased the demands and may have accelerated this drift toward earlier memory traces, thereby strengthening serial dependence. These observations are consistent with the results by Markov et al. (2024) who combined orientation adjustment trials with trials that contained a visual working memory task before the orientation adjustment task and also found that serial dependence was stronger when the current trial included an additional memory task. A similar increase in serial dependence was also reported if load itself is not manipulated but the length of the retention interval is increased (Bliss et al., 2017) which also aligns with the local attractor hypothesis by Panichello et al. (2019).

In Experiment 2 we found no difference in the strength of serial dependence between the different types of intermediate tasks. In each condition, the number of items, hence the load, was identical. We only manipulated the type of information observers had to compare on the intermediate task. These results suggest that when the comparison stimulus and the to-be-reproduced stimulus share a feature dimension, the strength of serial dependence was not affected, but a greater internal uncertainty (variability) was observed. In contrast, when the intermediate task involves distinct, non-overlapping features, the visual system compensates by increasing reliance on prior input, but without a loss in precision. Performance on a memory task often decreases with the number of items stored but also when items are similar, due to increased inter-item interference (Oberauer & Lin, 2017; Wennberg & Serences, 2024). Wennberg & Serences (2024) recently also reported that memory performance dropped when memory displays were homogeneous and contained only one type of stimulus feature compared to when a display was heterogeneous containing the same number of stimuli but two different stimulus features. They directly compared memory performance when four oriented lines (or four different colors) to be remembered to a display where two orientations and two colors had to be simultaneously remembered. Even though the number items remained identical, performance differed depending on how similar the four different items were. If the stimulus from the reproduction task and the stimulus from the intermediate task were the same, variability did increase, but the bias towards previous input was not affected highlighting that similarity mainly affects how precisely information is encoded and reported.

In Experiment 3, the intermediate task was an auditory comparison task. Here, we found that the strength of serial dependence again increased while we found no significant difference in response variability. When participants are required to perform an auditory memory task while remembering the orientation of the Gabor, attentional resources are split, and executive control becomes more limited. Under such conditions, it appears that the visual system relies more heavily on previously encoded information. Both visual and auditory tasks draw on a shared pool of working memory and attentional resources (Bae & Luck, 2017; Cowan, 2001; Klemen et al., 2010; Konstantinou et al., 2014; Liu et al., 2018; Saults & Cowan, 2007). When auditory demands occupy a substantial portion of these resources, the encoding of each visual trial becomes less precise, due to increasing internal noise. These results resemble the results obtained in the first experiment but the difference in serial dependence between the Control condition and the auditory condition was weaker than the difference in Experiment 1. It is important to note, however, that Experiment 3 involved a different group of observers, making it uncertain whether this weaker effect reflects a genuine difference between the two tasks or simply variability across participant samples.

Furthermore, our findings reveal that the increase in serial dependence observed between the Control and Circle/Auditory conditions cannot be attributed to changes in task difficulty when the intermediate task is added, as evidenced by the similar precision of participants' responses (i.e., comparable variability in adjustment errors). However, when the intermediate task involved the same feature dimension (orientation) as the one held in memory for reproduction, we did not observe an increase in serial dependence, but a small decrease in precision, reflected in higher response variability. Notably, these changes in variability occurred even though reaction time and accuracy were similar esp. across the Circle and Orientation conditions, ruling out that pure differences in task difficulty across the intermediate tasks cause the changes in variability.

In an additional analysis, we examined potential correlations between task performance and the strength of serial dependence. Overall, no systematic relationship was observed. Only in Experiment 1 we found a weak correlation indicating that observers who required longer response times tended to exhibit on average stronger serial dependence which resembles the results obtained by (Bliss et al., 2017) who showed that longer retention intervals lead to stronger serial dependence. However, this relationship was observed across participants (and not within observers as reported in Bliss et al., 2017). It is important to note that perceptual biases often show large individual differences. Such variability is commonly attributed to differences in sensory precision and the extent to which individuals rely on prior knowledge during perceptual processing (Glasauer & Shi, 2022; Zhang & Alais, 2020). Overall, we did not find a general pattern across participants in which task performance on the intermediate task correlated with serial dependence.

General role of WM and serial dependence

While our study showed an influence of memory on serial dependence, we did not conduct this study to directly examine the necessity of working memory in serial dependence, but our results show how working memory load has a modulational role in serial dependence, which does indeed speak in favour of a fundamental role of working memory in serial dependence as highlighted in previous work (Ceylan et al., 2021; Ceylan & Pascucci, 2023; Cheng, Chen, Glasauer, et al., 2024; Cheng, Chen, Yang, et al., 2024; Cheng et al., 2025; Feigin et al., 2021; C. Fischer et al., 2020; Fritsche et al., 2017; Houborg et al., 2023; Pascucci et al., 2019; Pascucci &

Plomp, 2021; Sheehan & Serences, 2022)

Together, our findings emphasize the critical role of working memory and feature-based interference in modulating how past and present information are integrated during perception and decision making.

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Author contributions

SHR designed and programmed the study. Testing and data collection were performed by BWR, ERG and RTH. BWR, ERG and RTH performed the data analysis under supervision of SHR. SHR wrote the manuscript, and BWR provided critical feedback. All authors approved the final version of the manuscript for submission.

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Competing Interests

The authors declare no competing interests.

Data availability

All data have been made publicly available via the Open Science Framework and can be accessed at https://osf.io/grzpv/

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