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Serial dependence in visual perception: A meta-analysis and review

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Positive sequential dependencies are phenomena in which actions, perception, decisions, and memory of features or objects are systematically biased toward visual experiences from the recent past. Among many labels, serial dependencies have been referred to as *priming*, *sequential dependencies*, *sequential effects*, or *serial effects*. Despite extensive research on the topic, the field still lacks an operational definition of what counts as serial dependence. In this meta-analysis, we review the vast literature on serial dependence and quantitatively assess its key diagnostic characteristics across several different domains of visual perception. The meta-analyses fully characterize serial dependence in orientation, face, and numerosity perception. They show that serial dependence is defined by four main kinds of tuning: serial dependence decays with time (temporal-tuning), it depends on relative spatial location (spatial-tuning), it occurs only between similar features and objects (feature-tuning), and it is modulated by attention (attentional-tuning). We also review studies of serial dependence that report single observer data, highlighting the importance of individual differences in serial dependence. Finally, we discuss a range of outstanding questions and novel research avenues that are prompted by the meta-analyses. Together, the meta-analyses provide a full characterization of serial dependence as an operationally defined family of visual phenomena, and they outline several of the key diagnostic criteria for serial dependence that should serve as guideposts for future research.

Introduction

Visual perception is serially dependent. What is perceived at this moment is systematically biased by—pulled toward—the visual experience in previous moments. Since the seminal studies in 2014 (Cicchini, Anobile, & Burr, 2014; Fischer & Whitney, 2014; Liberman, Fischer, & Whitney, 2014), a large number of studies have now documented that serial dependence occurs in the perceptual judgments of virtually all kinds of features and objects (Figure 1) and even more abstract impressions like emotion and attractiveness (Hsu & Yang, 2013; Kondo, Takahashi, & Watanabe, 2012; Liberman, Manassi, & Whitney, 2018; Taubert & Alais, 2016; Van der Burg, Rhodes, & Alais, 2019; Van der Burg, Toet, Brouwer, & Van Erp, 2021; Xia, Leib, & Whitney, 2016). Serial dependence is a family of phenomena (Figure 1), and it is thought to reflect underlying mechanism(s) that improve efficiency (Cicchini, Mikellidou, & Burr, 2018), accuracy (Cicchini et al., 2018), speed (Cicchini & Burr, 2018), and stability (Manassi & Whitney, 2022) of perception, decisions, memory, and motor reports.

Despite being found virtually everywhere in visual cognition, from orientation (Fischer & Whitney, 2014) to face recognition (Kondo et al., 2012; Liberman et al., 2014; Liberman et al., 2018; Turbett, Palermo, Bell, Hanran-Smith, & Jeffery, 2021; Van der Burg et al., 2019), and numerosity judgments (Cicchini et al., 2014; Corbett, Fischer, & Whitney, 2011; Fornaciai & Park, 2018b), the lines between other seemingly related phenomena like priming

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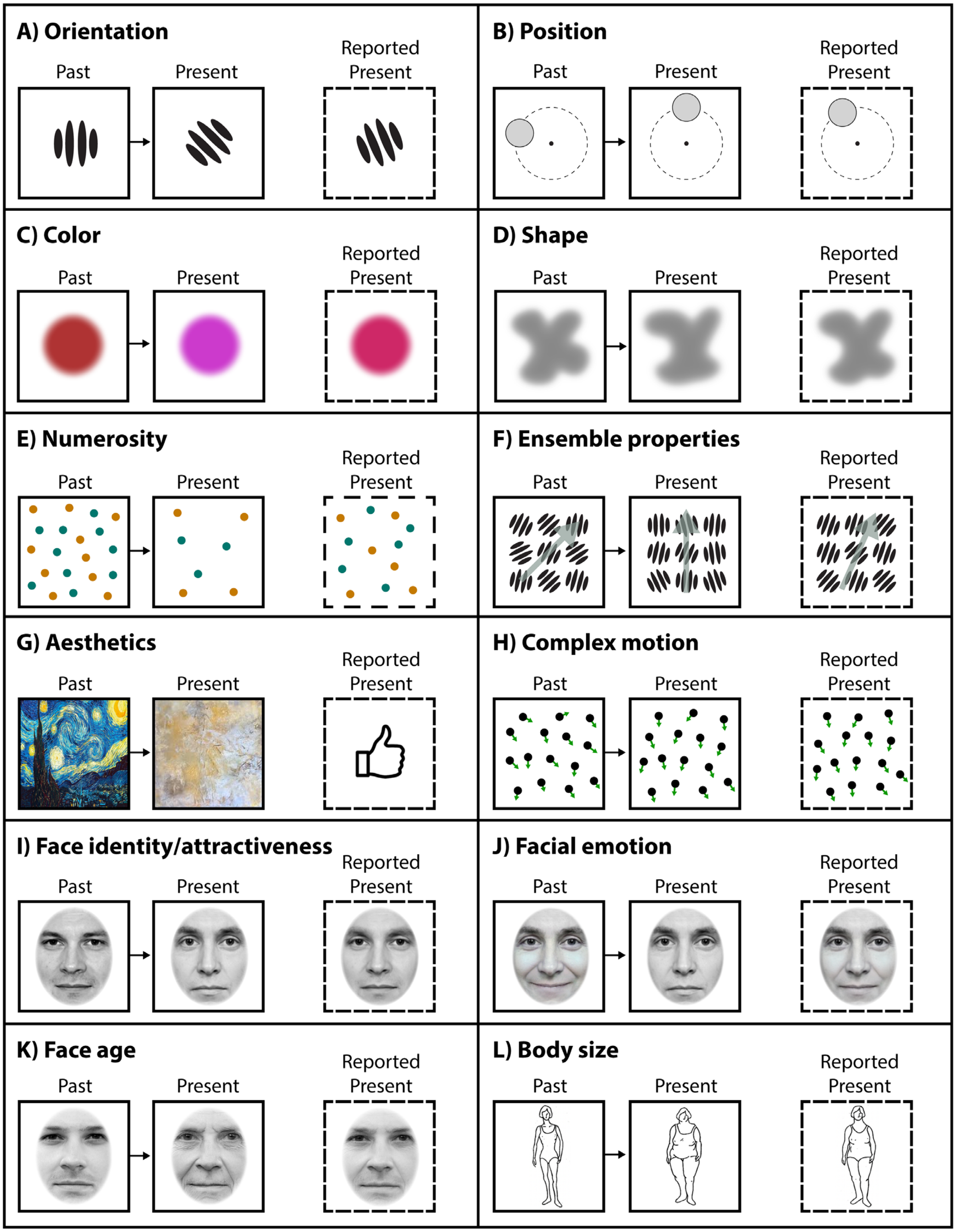

Figure 1. Positive serial dependencies across visual stimuli. In each panel, “Past” and “Present” frames refer to previous and current stimulus, respectively. The “Reported Present” frame refers to the reported current stimulus, biased by positive serial dependencies. (**A**) Serial dependence in orientation perception (Cicchini et al., 2017; Collins, 2019; Fischer & Whitney, 2014; Fritsche et al., 2017; Murai & Whitney, 2021; Pascucci et al., 2019). (**B**) Serial dependence in perceived/reported position, such that current locations appear more similar to those recently seen (Bliss et al., 2017; Manassi et al., 2018a; Papadimitriou et al., 2015). (**C**) Serial dependence in color judgments (Barbosa & Compte, 2020; Bays et al., 2009; Oberauer & Lin, 2017; Van den Berg et al., 2012). (**D**) Serial dependence in object shape (Collins, 2022b; Manassi et al., 2019, 2021). (**E**) Numerosity serial dependence, in which the current

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number of stimuli is biased toward previously experienced quantities (Cicchini et al., 2014; Corbett et al., 2011; Fornaciai & Park, 2018a; Fornaciai & Park, 2018b). (**F**) Serial dependence in ensemble average judgments (gray arrows indicate the ensemble orientation; (Collins, 2022a; Manassi et al., 2017; Pascucci et al., 2019). (**G**) Serial dependence in complex motion patterns (Czoschke, Fischer, Beitner, Kaiser, & Bledowski, 2019; Fischer et al., 2020) and (**H**) aesthetic ratings are reported as biased toward previous visual stimuli (Kim et al., 2019). (**I–L**) In the domain of people-perception, face identity (Liberman et al., 2014; Taubert et al., 2016a; Turbett et al., 2021; Turbett et al., 2022b), emotion (Hsu & Wu, 2020; Hsu & Yang, 2013; Liberman et al., 2018; Mei et al., 2019), age (Clifford et al., 2018; Manassi & Whitney, 2022), gaze (Alais et al., 2018) and body size (Alexi et al., 2018) are reported as biased toward previously seen individuals. Images in L are taken from Stunkard Figure Rating Scale. Faces in I, J, and K are AI generated.

(Galluzzi, Benedetto, Cicchini, & Burr, 2022) remain persistently murky. This reveals a lack of mutual understanding about what "serial dependence" is and what it is not, and, unfortunately, this hinders the questions and debates about the possible functional purposes of serial dependencies in general: if serial dependence is not operationally defined, then its computational goal cannot be addressed. Several recent reviews highlight this lack of agreement (Hsu, 2021; Kiyonaga, Scimeca, Bliss, & Whitney, 2017; Pascucci et al., 2023).

We believe the field fundamentally lacks an operational definition of serial dependence. Part of the difficulty in establishing an operational definition arises because most publications start with theoretical motivations, but the premises of these theories are not universally agreed upon. On the other hand, there is now a substantial amount of empirical and quantitative data that has been published on serial dependence. Given the extensive empirical data, our aim here is to construct a set of meta-analyses to bootstrap the diagnostic criteria for serial dependence.

The goal of this meta-analysis is to condense a large number of published studies on serial dependence, and quantitatively assess its key diagnostic characteristics across several different domains of visual perception. We will start with an exploration of those characteristics that are commonly tested and associated with serial dependence, including (1) temporal-tuning, (2) spatial-tuning, (3) feature-tuning, and (4) attention-tuning. Temporal tuning is the fading of serial dependence with time (Bilacchi, Sirius, Cravo, & de Azevedo Neto, 2022; Bliss, Sun, & D'Esposito, 2017; Fischer & Whitney, 2014; Fritsche, Spaak, & de Lange, 2020). Spatial tuning is the fading of serial dependence with increasing spatial distance between sequential objects (Collins, 2019; Fischer & Whitney, 2014; Fornaciai & Park, 2018b; Luo, Zhang, & Luo, 2022). Feature tuning is the finding that serial dependence occurs for more similar sequential objects but not for dissimilar ones (Barbosa & Compte, 2020; Fischer & Whitney, 2014; Liberman et al., 2014; Turbett et al., 2021), and attention tuning refers to the fact that serial dependence decreases with decreasing attentional resources devoted to previously experienced stimuli (Fischer & Whitney, 2014; Fritsche & de Lange, 2019; Kim, Burr, Cicchini, & Alais, 2020; Rafiei, Hansmann-Roth, Whitney, Kristjansson, & Chetverikov, 2021b). Although these characteristics were qualitative descriptions in previous articles, there are now enough published studies on serial dependence to build a quantitative meta-analysis of these factors.

To foreshadow, the meta-analyses reported here demonstrate a striking consistency across studies; they provide a means of contextualizing specific studies and future work within the broader landscape of serial dependence research. More importantly, the meta-analyses reveal several concrete diagnostic criteria for what counts as serial dependence, and they raise new questions and avenues of investigation. The meta-analyses also highlight several surprising differences and structural issues with research on serial dependence, along with hints toward improving the efficiency of future experiments and the importance of individual differences.

Methods

Study selection and exclusion criteria

To identify appropriate articles for our meta-analyses, we searched across several online electronic databases (e.g., Google Scholar, PubMed) using various combinations of relevant search terms: "serial dependence," "serial effect," "sequential effect," and "sequential dependence" (and corresponding plural terms). Moreover, further studies were found by means of the "related articles" function of the PubMed/Google Scholar database and by tracing the references from review articles and the identified studies. Throughout this review, we refer to positive serial dependencies as simply "serial dependence," phenomena in which actions, perception, decisions, and memory of features or objects are systematically biased toward visual experiences from the recent past. This attractive bias is in contraposition with negative aftereffects (Kohn, 2007; Thompson & Burr, 2009; Webster, 2012), a known form of repulsive bias following adaptation.

For the purpose of our meta-analysis, we adopted the following exclusion criteria: (A) We included only articles that claimed to be studying serial dependence (or related terms, see above), not every article on every history effect in the perception and memory literature. There were several reasons for this. First, pragmatically, this is a clear-cut delineation that limits the number of articles to a tractable set. Second, one should not presuppose that any form of priming, hysteresis, proactive interference, or other history effect is, in fact, serial dependence. Instead, we rely on the studies themselves to make a claim of serial dependence. Third, and most importantly, having a meta-analysis of the set of studies that claim to investigate serial dependence allows us to go back and evaluate whether any other particular study (even one published before the term "serial dependence" was coined) conforms to the operational definition of serial dependence. In this way, we can still evaluate whether various phenomena such as "priming-of-pop-out" (Maljkovic & Nakayama, 1994; Maljkovic & Nakayama, 1996) or concepts such as "object files" (Kahneman, Treisman, & Gibbs, 1992; Treisman, 1986) are, in fact, forms of serial dependence. (B) Studies that were not peer-reviewed were not considered for the purpose of our meta-analyses.[1] (C) Published articles were included in the meta-analysis if they contained data or summary statistics sufficient to recover effect size estimates or other indexes. In total, we included more than 100 publications across our meta-analyses. The specific number of studies considered for the separate meta-analyses are reported in each section, respectively.

Data analysis

We computed a variety of indexes across studies: the strength of serial dependence (using amplitude measures and effect size estimates such as Fisher z_r), the stimulus similarity for which serial dependence peaks, the frequency of serial dependence across participants, and the number of trials and observers in each study. The strength of serial dependence was computed using amplitude measures or effect size estimates reported in each study (e.g., corresponding *f*-test, *t*-test with degrees of freedom, equivalent 95% confidence intervals and means, or *p*-values, if no other statistic was reported). These scores were then transformed into correlation coefficients (McGrath & Meyer, 2006; Rosenthal & Rubin, 2003) and converted into Fisher z_r scores (weighted by the sample size of each study) to normalize the distribution (Rosenthal & DiMatteo, 2001). We computed Fisher z_r because (1) it is a well understood metric linearized version of r (Rosenthal & DiMatteo, 2001), (2) it is more flexible than variants of Cohen d (or Hedges g, or Glass delta, etc.) (Goulet-Pelletier and Cousineau 2018; McGrath and Meyer 2006), (3) and it can be calculated for more different designs especially when there are very substantial differences between studies (McGrath & Meyer, 2006).

In each section, published articles were included if they contained data or summary statistics sufficient to recover effect size estimates or other measures. When statistical tests and corresponding effect sizes were reported in the original papers, we used those. When unavailable, we used *r*-equivalent scores (Rosenthal & Rubin, 2003) and *r*-contrast scores (Rosenthal & DiMatteo, 2001) derived from *p*-values and corresponding Z and X^2 scores. For studies that reported individual differences, we collected cumulative totals and calculated X^2 scores. No known published articles were excluded that included quantitative effect sizes for serial dependence, available at the time of the analysis. Each published article was only counted once, such that study was a random effect. Studies were not weighted based on any subjective criteria such as "study quality" (Rosenthal, 1995).

Results

Our primary goal was to provide a meta-analysis of the types of selectivity that have been reported for serial dependence in several different domains, including orientation perception (Figure 2), face perception (Figure 3), and numerosity perception (Figure 4). Serial dependence has been reported in several other domains as well (Figure 1), but the number of studies within each is limited.

There are several ways in which serial dependence is reported to be selective. The four most common types of selectivity proposed in the literature are (1) temporal tuning, (2) spatial tuning, (3) feature tuning, and (4) attention tuning. However, not all studies report each of these characteristics, and thus there is debate regarding their existence and specific properties. Additionally, it is unclear whether each of these holds in the same way across different domains (e.g., orientation and face serial dependence). The lack of clarity and diversity of opinion highlights the potential value of meta-analyses of these tuning properties.

In addition to the possible tuning of serial dependence, several studies showed that serial dependence might depend on other factors such as uncertainty and noise (Gallagher & Benton, 2022; Kim & Alais, 2021; Manassi, Liberman, Kosovicheva, Zhang, & Whitney, 2018a; Manassi & Whitney, 2022; Pascucci et al., 2019; van Bergen & Jehee, 2019), as well as memory delay (Bliss et al., 2017; Fritsche, Mostert, & de Lange, 2017). There are also possible interactions between these moderating variables. For example, it may be that the temporal tuning differs depending on the stimulus (Taubert, Alais, & Burr, 2016a), or the spatial tuning might vary for different tasks or levels

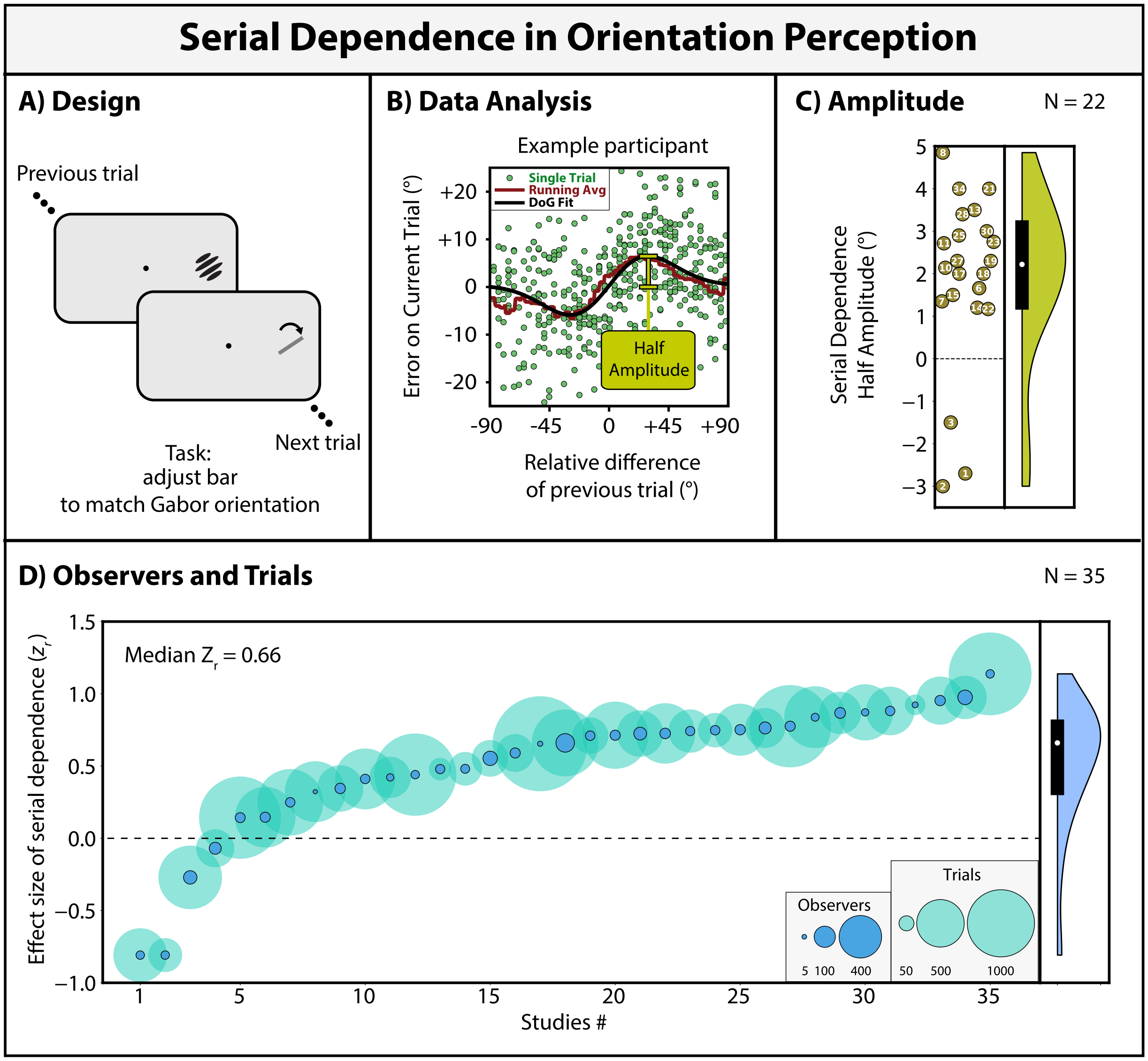

Figure 2. Serial dependence in orientation perception. (**A**) Serial dependence is a pull in perceptual judgments toward previously experienced features, objects, or, in this case, orientations. For example, the perceived orientation on trial N is pulled toward the orientation seen on trial N-1. Here, a continuous report match-to-sample task is depicted, but many different psychophysical designs have revealed serial dependence in orientation perception, including method of constant stimuli, magnitude estimation, detection, and others. (**B**) Serial dependence is often (although not always) measured by fitting a DoG- or derivative-of-von-Mises–shaped function to the data and measuring the amplitude of the function. The x-axis in such graphs is the difference in sequential stimulus orientation. The y-axis is some measure of error in perceptual judgment. The positive slope in the DoG function indicates a positive capture, such that clockwise orientations on trial N-1 cause the orientation on trial N to seem more clockwise. The slope is steepest at 0, indicating that serial dependence is strongest (most efficient) for sequentially similar objects. (**C**) Half-amplitude of orientation serial dependence across 22 studies. Positive values indicate attraction towards the past, whereas negative values indicate repulsion from the past. Each dot represents the amplitude of serial dependence reported in a single published article. Nineteen of 22 publications that measured SD reported it was positive ($X^2(1) = 11.6$, $p < 0.001$). The median SD half-amplitude is 2.22°. Numbers in each dot refer to the study number in the next panel. The half violin plot indicates the median (white circle), interquartile ranges (black rectangles) and the density distribution (green shape). Individual study numbers (see below) are more clearly visible in the electronic version of the document. (**D**) Not all studies that measure serial dependence in orientation measured or reported amplitude. The effect size (Fisher z_r) of serial dependence for 35 studies, ranked; given the different measure of serial dependence, more studies were available for this meta-analysis. The median effect size is 0.66 (Fisher z_r). The studies in panel (C) are a subset of those in panel (D). The area of the teal-green dot represents the relative number of trials per subject. The size of the smaller blue dot at the center of the green dot represents the relative subject-sample size (N) of each study. Some studies used a small observer pool but large trial count, and some studies used larger N observers (indicated by larger blue dots). The half violin plot indicates the

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median (white circle), interquartile ranges (black rectangles) and the density distribution (blue shape). Studies ranked along the abscissa are 1 (Bae & Luck, 2019) 2 (Bae & Luck, 2017) 3 (Ceylan et al., 2021) 4 (Bosch et al., 2022) 5 (Murai & Whitney, 2021) 6 (Fritsche et al., 2020) 7 (Pascucci et al., 2019) 8 (Fischer & Whitney, 2014) 9 (Myers et al., 2018) 10 (Gallagher & Benton, 2022) 11 (Collins, 2019) 12 (Galluzzi et al., 2022) 13 (Cicchini et al., 2021) 14 (van Bergen & Jehee, 2019) 15 (Teng et al., 2022) 16 (Wildegger et al., 2015) 17 (Cicchini et al., 2018) 18 (Kondo et al., 2022) 19 (Samaha et al., 2019) 20 (M. Luo et al., 2022) 21 (Abreo et al., 2023) 22 (Fritsche et al., 2017) 23 (Lau & Maus, 2019) 24 (Rafiei et al., 2021b) 25 (Ceylan et al., 2021) 26 (Gekas et al., 2019) 27 (Cicchini et al., 2017) 28 (Manassi et al., 2017) 29 (Zhang & Alais, 2020) 30 (Liberman et al., 2016) 31 (Rafiei et al., 2021a) 32 (Mikellidou et al., 2021) 33 (John-Saaltink et al., 2016) 34 (Sheehan & Serences, 2022) 35 (Kim et al., 2020).

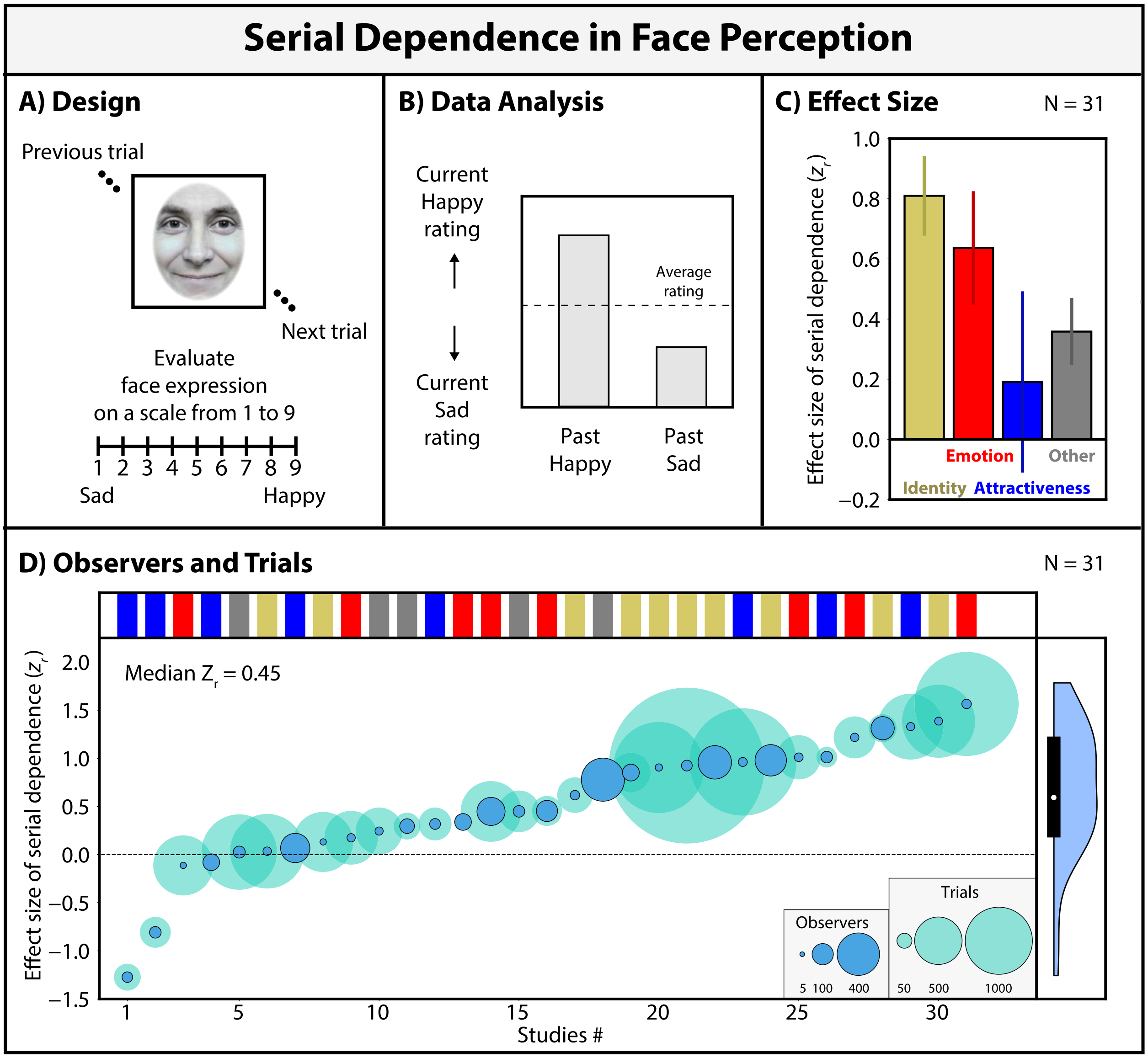

Figure 3. Serial dependence in face perception. (**A**) An example task in which the perceived facial expression (or emotional expression or attractiveness) on trial N is pulled toward the face (attractiveness, emotion, or identity) seen on trial N-1. Serial dependence in face perception is measured using a variety of techniques including Likert ratings, classification, forced choice procedures, method of constant or single stimuli, and continuous report adjustment tasks, among other approaches. (**B**) Observer judgment biases are typically calculated conditionally on previous stimuli. In the example above, when the previous trial has a happy face, the rating on the current face is more likely to be happy. Conversely, when the previous trial displays a sad face, the rating on the current face is more likely to be sad. (**C**) Serial dependence in the perception of faces has been measured for a variety of face attributes including

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identity, emotion, attractiveness, gaze, age, gender, among other dimensions. Error bars indicate standard error from the mean. The effect sizes (Fisher z_r) of serial dependence in face perception varies across studies in face identity (gold, $N = 10$), face emotion (red, $N = 8$), face attractiveness (blue, $N = 8$), and other face attributes (gray, $N = 5$; age, gender, gaze). (**D**) The effect size (Fisher z_r) of face serial dependence for 30 studies, ranked; The area of the green dot represents the relative number of trials per subject. The size of the smaller blue dot at the center of the green dot represents the relative subject-sample size (N) of each study. Some studies used a small observer pool but large trial count, and some studies used larger N observers (larger blue dot). Bar colors in the panel above the scatter plot indicate the face feature investigated (identity = gold; emotion = red; attractiveness = blue; other = gray). The half violin plot indicates the median (white circle), interquartile ranges (black rectangles) and the density distribution (blue shape). Studies ranked along the x-axis are 1 (Huang et al., 2018), 2 (Pegors et al., 2015), 3 (Taubert et al., 2016a), 4 (Kramer & Pustelnik, 2021), 5 (Yu & Ying, 2021), 6 (Bell et al., 2020), 7 (Xia et al., 2016), 8 (Taubert et al., 2016a), 9 (Alais et al., 2021), 10 (Alais et al., 2018), 11 (Starks et al., 2020), 12 (Ho & Newell, 2020), 13 (Hsu & Wu, 2020), 14 (Ortega et al., 2023), 15 (Clifford et al., 2018), 16 (Van der Burg et al., 2021), 17 (Kok et al., 2017), 18 (Manassi & Whitney, 2022), 19 (Turbett et al., 2021), 20 (Kim & Alais, 2021), 21 (Liberman et al., 2014), 22 (Turbett et al., 2022a), 23 (Taubert & Alais, 2016), 24 (Turbett et al., 2019), 25 (Liberman et al., 2018), 26 (Kondo et al., 2013), 27 (Mei et al., 2019), 28 (Turbett et al., 2022b), 29 (Van der Burg et al., 2019), 30 (Hsu & Lee, 2016), 31 (Collins, 2022b).

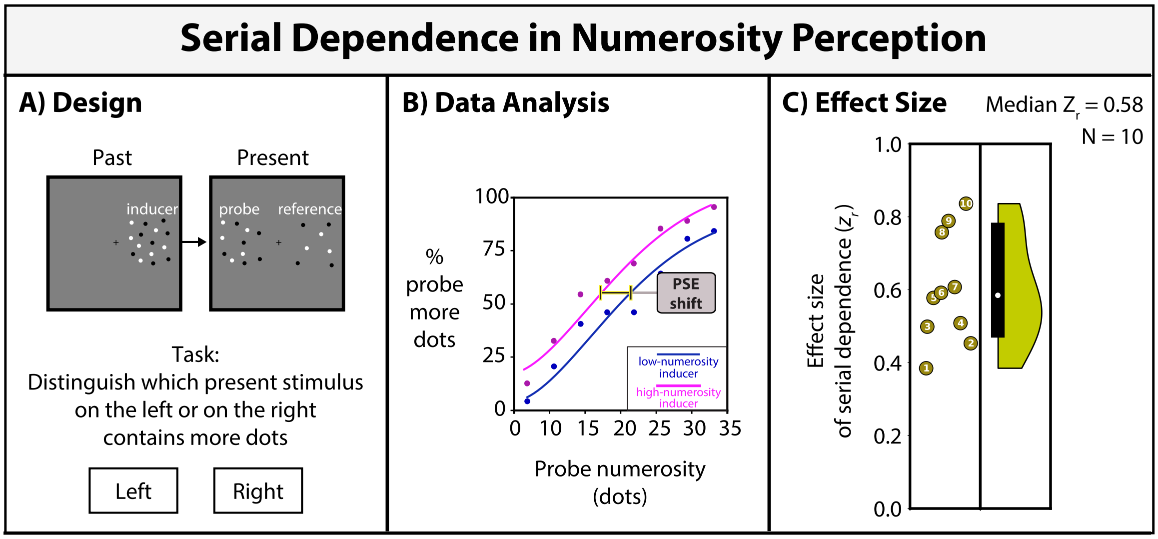

Figure 4. Serial dependence in numerosity perception. (**A**) An example numerosity serial dependence discrimination task. Observers are asked to continuously fixate a central cross, and are presented with an array of dots (inducer) on one side. Next, they are presented with two dot arrays on each side (probe and reference). Observers are then asked which array (probe and reference) contains more dots (2AFC task, Left/Right). Other experimental designs are also used to measure numerosity serial dependence, including magnitude estimation and others (not shown). (**B**) The Lines indicate the psychometric curve fits to individual subjects' two-alternative-forced-choice data with a low (blue) or high (violet) numerosity previous inducer. The inducer alters the perceived numerosity of the probe stimulus, shifting the point of subjective equality (PSE) for the simultaneously presented dots array in the present. The direction of the PSE shift indicates a positive serial dependence. (**C**) Effect size of numerosity serial dependence across 10 studies. Positive values indicate attraction towards the past, whereas negative values indicate repulsion from the past. Each dot represents the effect size of serial dependence reported in a single published paper. All 10/10 publications that measured serial dependence reported it was positive. The median effect size is 0.58. Numbers in each dot refer to the study number below, and are more clearly visible in the electronic version of the document. The half violin plot indicates the median (white circle), interquartile ranges (black rectangles) and the density distribution (yellow shape). Studies ranked along the y-axis are 1 (Fornaciai & Park, 2019a), 2 (Fornaciai & Park, 2019b), 3 (Togoli et al., 2021), 4 (Fornaciai & Park, 2020b), 5 (Fornaciai & Park, 2018b), 6 (Fornaciai & Park, 2020a), 7 (Fornaciai & Park, 2018a), 8 (Corbett et al., 2011), 9 (Fornaciai & Park, 2022), 10 (Cicchini et al., 2014).

of processing. The possibility that serial dependence occurs at multiple stages (Kiyonaga et al., 2017; Liberman et al., 2014; Manassi et al., 2018a) highlights the importance of these interactions. Subdividing the studies on serial dependence yields relatively few studies for each interaction. Although a meta-analysis is technically feasible with just two studies (Rosenthal & DiMatteo, 2001; Rosenthal & Rubin, 2003), caution is warranted when interpreting the interactions at such a fine-grain. We therefore focus our meta-analyses on a few core areas where there are a substantial number of papers. These include orientation (Figure 2), face identity, expression, and attractiveness (Figure 3), as well as numerosity (Figure 4).

Serial dependence in orientation perception

The most commonly studied type of visual serial dependence is orientation perception. Figure 2A shows a typical paradigm used to investigate serial dependence in this domain: observers are usually presented with a sequence of randomly oriented Gabor patches, and they are asked to adjust a bar to match the orientation of the Gabor on each trial (Figure 2A). In one commonly used data analysis approach, errors in orientation judgments are plotted relative to the difference between sequential stimulus orientation (Figure 2B), yielding a characteristic Derivative-of-Gaussian (DoG) shape. Many studies fit a function essentially equivalent to this (Liberman et al., 2018; Manassi, Kristjánsson, & Whitney, 2019; Rafiei et al., 2021b), or model-free approach (Ceylan, Herzog, & Pascucci, 2021; Samaha, Switzky, & Postle, 2019). The half amplitude of this function is often taken as a simple metric of the serial dependence strength (Figure 2B).

Figure 2C shows serial dependence in orientation perception in degrees of rotation for 22 studies that reported serial dependence in terms of amplitude (degrees of rotation). There is substantial agreement across studies, with a median half-amplitude serial dependence of 2.21 deg. There are three clear outliers (each more than 1.7 Z units below the mean). These three studies used stimuli that were either very different from standard low contrast Gabors (Bae & Luck, 2017; Bae & Luck, 2019) or were strings of multiple stimuli (Ceylan et al., 2021), unlike typical studies of orientation serial dependence.

Not all studies that investigate serial dependence used or reported the DoG-equivalent amplitude in degrees of rotation; Figure 2D shows the effect size of serial dependence in orientation reported in 35 separate publications across different serial dependence measures. The overall effect size was substantial (median Fisher $z_r = 0.66$), and the agreement was high ($sem = 0.077$). To address statistical significance, we performed a Stouffer test (Kim et al., 2013) combining z-scores from each study into a single test statistic ($Z = 28.2$, $p < 0.0001$). Across studies, there was variability in the number of observers recruited for each study (ranging from four to 76, represented by the size of the blue dot), and just as much variability in the number of trials collected from each participant (represented by the size of the green circle in Figure 2, from 96 to ∼2000 trials per observer). As r-equivalent and r-contrast (Rosenthal & Rubin, 2003) can overestimate true population effect size (Dunlap, Cortina, Vaslow, & Burke, 1996; Lakens, 2013), and not all studies reported sufficient information to recover sample or population standard deviations, we also computed a simple and conservative vote count test, which shows the obvious fact displayed in Figure 2, that there is a highly significant overall serial dependence effect ($X^2(1) = 20.8$, $p < 0.0001$).

Serial dependence in face perception

The second most commonly studied type of visual serial dependence is face perception. Figure 3A shows a typical paradigm used to investigate serial dependence in this domain: observers are presented with a sequence of faces, and they are asked to estimate the magnitude of a specific face feature on each trial (Figure 3A, facial expression). Ratings are biased depending on the face content in previous trials, thus showing that face perception is biased toward the past (Figure 3B).

The serial dependence literature in this domain can be broken down into different face attributes (Figure 3C). The three most common forms of serial dependence in face processing that have been studied are face identity, face expression (e.g., emotion or affect), and face attractiveness, as well as other face features such as age, gaze, gender, and more. Interestingly, the effect sizes for these forms of serial dependence are quite different from one another (Figure 3C). Face identity perception shows the strongest and most consistent serial dependence (Stouffer method; $Z = 26.0$, $p < 0.0001$). Face expression is somewhat weaker ($Z = 13.7$, $p < 0.0001$). Face attractiveness has a very broad (nearly bimodal) range of reported effect sizes across studies (including most of the negative effect sizes in Figure 3D). Nevertheless, there is still a significant net positive serial dependence in attractiveness judgments ($Z = 2.0$, $p = 0.022$). Figure 3C raises many questions. For example, does serial dependence vary for different types of face processing in a manner that reflects the needs of the representational system, an idea that has been previously raised (Taubert et al., 2016a)? One may think of attractiveness as a stable trait, but on a moment-to-moment basis, there is substantial variation in the attractiveness of any given identity (e.g., the frozen face effect; Post, Haberman, Iwaki, & Whitney, 2012). Whether serial dependence is tuned to the temporal statistics of different face attributes is an open and exciting question, but there are growing hints this might be the case, at least for emotional expression (Ortega, Chen, & Whitney, 2023). Another possibility is that serial dependence varies because of differences in sensitivity to face identity versus attractiveness.

Figure 3D shows an overview of 31 studies that measured serial dependence in some form of face processing (e.g., perceived identity, expression, attractiveness, age, gender, etc.). As with serial dependence in orientation perception, the effect size is very large (median Fisher $z_r = 0.45$; Stouffer method, $Z = 28.7$, $p < 0.0001$). Agreement across studies is generally high ($sem = 0.122$), with two outliers in this group (each of which is more than 1.7 Z units from the mean), but these were not excluded from the analysis. Across studies, we observed variability in the number of observers recruited for each study (ranging from nine to 412, represented by the size of the blue dot), and just as much variability in the number of trials collected from each participant (represented by the size of the green circle in Figure 3, from 1 to 5382 trials per observer).

Serial dependence in numerosity perception

Figure 4 shows a meta-analysis of serial dependence in numerosity perception. In a typical paradigm used to investigate serial dependence in this domain (Fornaciai & Park, 2018b), observers are first presented with dot-array stimuli of varying numerosities on one side of the visual field (inducer). Next, they are presented with two arrays on each side (probe vs reference), and they are asked to report which side contained the larger number of dots (Figure 4A). The psychometric function for numerosity discrimination is typically shifted in the presence of a prior inducer (Figure 4B), such that current numerosity estimates are pulled toward quantities previously experienced. Figure 4C shows an overview of serial dependence studies in numerosity perception (10 studies; median Fisher $z_r = 0.58$; Stouffer method, $Z = 9.14$, $p < 0.0001$) with high agreement across studies ($sem = 0.05$).

Statistical power in studies of serial dependence

Serial dependence in both orientation (Figure 2) and face perception (Figure 3) has been reported in many studies, but it is noteworthy that the sample sizes are often relatively small. In part, this is because some authors have analyzed and presented data at the single-participant level, opting to collect many trials for single observers (e.g., small blue dots relative to larger green circles in Figures 2 and 3). This is a familiar practice in vision science. Other authors have chosen to pool all subjects together into a single super-subject (effectively treating their sample as a single observer). One study collected thousands of independent observers, with each observer participating in one single trial (Manassi & Whitney, 2022). There are clearly different approaches across studies, but, despite that, there is still a great deal of consistency and a clear picture emerges: larger powered (i.e., larger sample size) studies provide more reliable measures of serial dependence. Figure 5 shows funnel plots for orientation, face, and numerosity serial dependence. The general trend is what one would expect, with the largest powered studies revealing most clearly what the overall median effect size is. The smallest and largest effect sizes are typically carried by lower powered studies. Although there is no obvious sign of publication bias, there are relatively few studies on numerosity serial dependence and the resulting gap in the funnel plot (Figure 4C) highlights the need for more studies in this domain. The takeaway message from the funnel plots is that more studies are needed with larger sample sizes.

Properties of serial dependence: Temporal tuning

Serial dependence is, at its heart, a bias in the perceptual judgments of observers, such that the current experience is pulled toward previously experienced stimuli. Naturally, most studies of serial dependence report some form of temporal modulation; for example, by examining from how many trials into the past the bias originated, or the effect of the inter-stimulus interval (Bilacchi et al., 2022; Bliss et al., 2017; Fischer & Whitney, 2014; Fritsche et al., 2020; Manassi et al., 2019; Suárez-Pinilla, Seth, & Roseboom, 2018). This raises many questions. First, is there, in fact, temporal tuning in serial dependence? Does the current perceptual judgment depend on all previous objects and features (a kind of global central tendency) or is serial dependence tuned toward the most recently seen ones? Is serial dependence tuned to time or is it tuned to the number of intervening trials (or both)? Is the temporal tuning of serial dependence contingent on the nature of the stimulus, and does it follow something about the natural scene statistics of that stimulus class? Some of these questions are approachable with meta-analytic techniques. Some are not, yet, because of the limited number of studies.

Figure 6A shows the temporal tuning of serial dependence (across all kinds of visual stimuli) as a function of the number of intervening trials. Figure 6B shows available studies plotted as a function of intervening time. Our meta-analysis reveals a clear form of temporal tuning: serial dependence weakens over time (or trials) and has a time constant that is approximately 12 to 20 seconds or three to five trials (boostrapped median regression line; p value < 0.001). This body of results is in accordance with the seminal study from Fischer & Whitney (2014). It is tempting to directly compare the graphs in Figures 6A and 6B (time vs trials), but it is not clearly fair to do so because many of the underlying experiments were designed in a way that confounded trials and time, making them collinear.

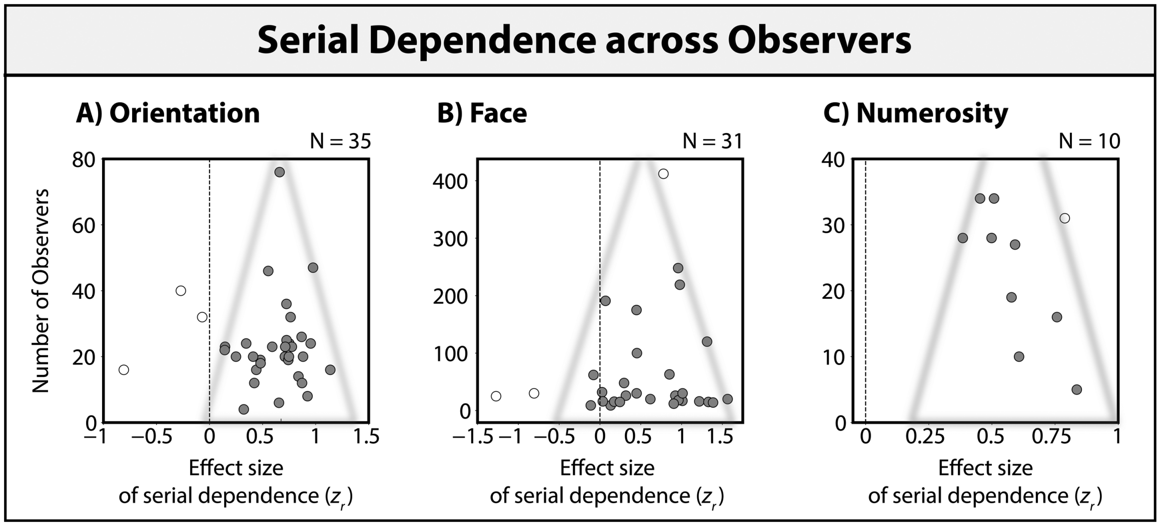

Figure 5. Funnel plots for serial dependence in orientation (**A**), face (**B**), and (**C**) numerosity perception. The average number of observers in each study (y-axis, a proxy for statistical power) is plotted against the corresponding effect size of each study (x-axis). Isosceles triangles were centered at the median of the effect size for each domain (orientation/face/numerosity) and encompassed 90% of the studies (individual circles). Vertical dashed line indicates null effect size. The studies in orientation (**A**) and face (**B**) domains generally fall within a funnel or triangular shaped pattern, as would be expected. White circles indicate studies outside of the 90% inclusion boundaries, but these are not necessarily outliers in terms of effect size (Figures 2–4). There are fewer studies on serial dependence in numerosity perception (**C**), and despite showing a very strong effect overall, the funnel plot highlights that studies have a more limited range of sample sizes. Although there is no obvious sign of publication bias, there are some gaps evident, especially in the numerosity serial dependence funnel plot (**C**), suggesting that more studies with larger sample sizes are needed.

Furthermore, there are different studies included in Figure 6A versus Figure 6B (see caption). Some studies tried to dissociate time and trials, and the results suggest that both time and intervening information (trials) may matter (Bilacchi et al., 2022; Bliss et al., 2017; Fritsche et al., 2017; Papadimitriou, Ferdoash, & Snyder, 2015; Wexler, Duyck, & Mamassian, 2015). In any case, our analysis reveals a clear form of temporal tuning, such that more recent stimuli are weighted more heavily in current perceptual judgments. It is important to mention that temporal tuning—as with other types of tuning— is continuously modulated by several factors such as relative spatial location (Fischer & Whitney, 2014), feature similarity, attention, decision, memory (Bliss et al., 2017; Fritsche et al., 2017), and confidence (Samaha et al., 2019) and thus should not be considered as a strictly rigid or fixed temporal window. Interestingly, some studies also reported biases for long time distances; Gekas, McDermott, and Mamassian (2019) found that perception was attracted toward the very recent past, repulsed from stimuli at medium timescales and slightly attracted to presentations further in the past; Fritsche et al. (2020) found a repulsion bias from stimuli experienced up to minutes into the past. Additional future research is needed to conduct a meta-analysis that will clarify the presence and long-term temporal dynamics of these effects.

Temporal tuning of serial dependence in other domains, such as orientation (Figure 6C), numerosity, position, color, shape, and face perception (Figure 6D) are rarely investigated. Of these, serial dependence in face perception is most frequently reported, with 14 studies demonstrating temporal tuning (Figure 6D). However, these are distributed across different face attributes (identity, emotion, and attractiveness) and Figure 3 indicated that serial dependence for different face attributes may be dissociable. Therefore the temporal tuning of serial dependence may be different for different face attributes (Ortega et al., 2023; Taubert et al., 2016a). There is clearly temporal tuning in different domains, but more studies are required within each domain for comparative meta-analytic purposes.

Properties of serial dependence: Spatial tuning

Another commonly manipulated independent variable in studies of serial dependence is the spatial position of sequential objects (Figure 7A). In many studies, shifting the location of sequential objects

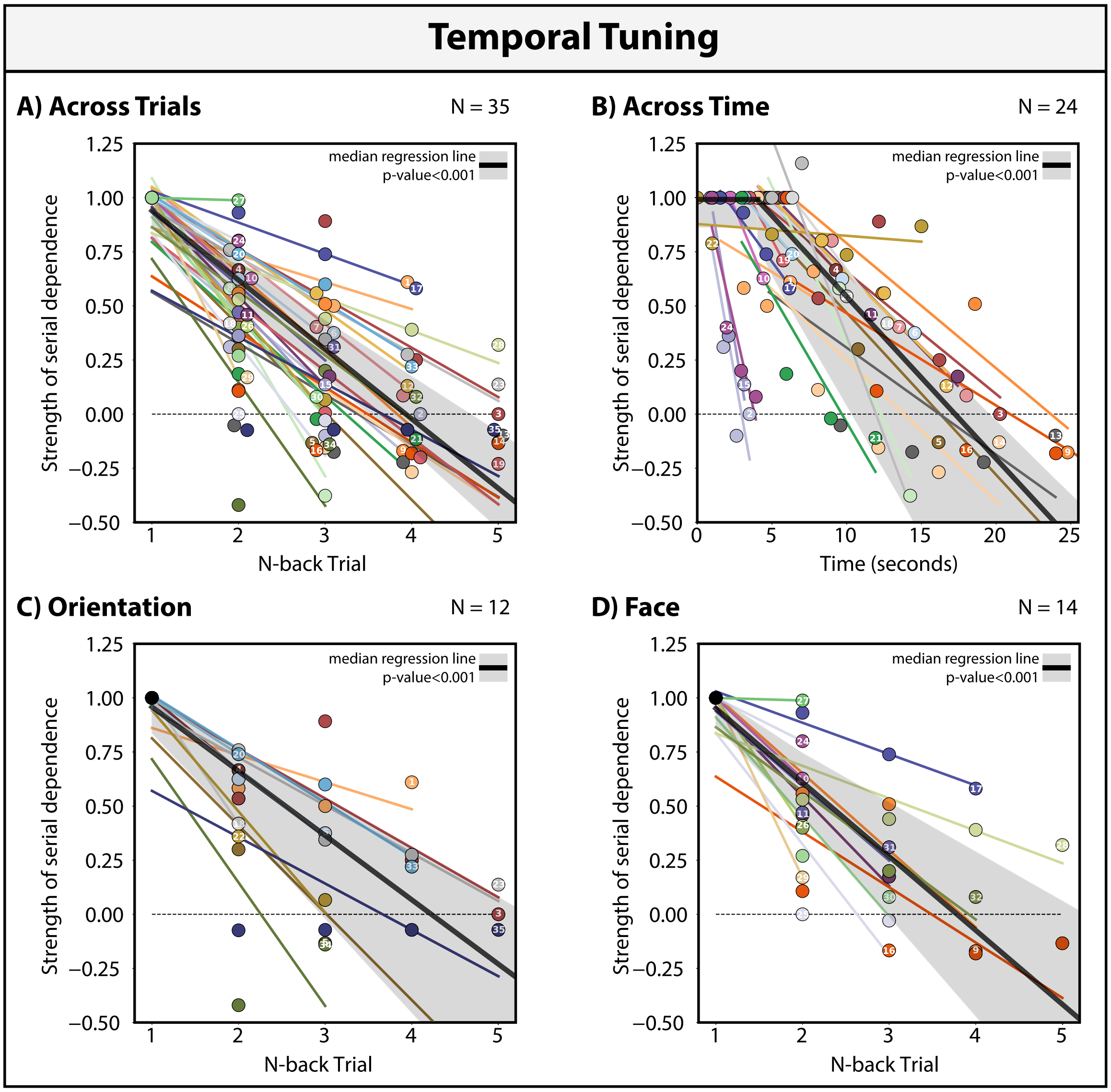

Figure 6. Temporal tuning of serial dependence. (**A**) We computed serial dependence strength across intervening n-back trials (x-axis). Dots were jittered around the n-back trial for illustration purposes. Y-axis shows the strength of serial dependence (positive values indicate serial dependence, negative values indicate negative aftereffect); we normalized the strength of serial dependence dividing by the strength of serial dependence in the 1-back condition for each study. For each study ($N = 32$), we computed the predicted regression line across n-back trials. The black line shows the median bootstrapped regression line. Shaded grey error bars indicate 95% Confidence Interval across studies. Serial dependence strength gradually decayed with increasing the number of trials. Reviewed studies are 1 (Collins, 2020), 2 (Collins, 2022b) shape stimuli, 3 (Lau & Maus, 2019), 4 (Manassi et al., 2017), 5 (Fritsche et al., 2017), 6 (Fischer & Whitney, 2014), 7 (Manassi et al., 2018a), 8 (Manassi et al., 2021), 9 (Liberman et al., 2018), 10 (Hsu & Wu, 2020), 11 (Mei et al., 2019), 12 (Manassi et al., 2019), 13 (Fornaciai & Park, 2020b), 14 (Fornaciai & Park, 2022), 15(Alais et al., 2017), 16 (Xia et al., 2016), 17 (Taubert & Alais, 2016), 18 (Collins, 2019), 19 (Suárez-Pinilla et al., 2018), 20 (Kondo et al., 2022), 21 (Van der Burg et al., 2021), 22 (Rafiei et al., 2021b), 23 (Zhang & Alais, 2020), 24 (Alais et al., 2021), 25 (Ho & Newell, 2020), 26 (Hsu & Lee, 2016), 27 (Bell et al., 2020), 28 (Van der Burg et al., 2019), 29 (Van der Burg et al., 2021), 30 (Taubert et al., 2016b), 31 (Ortega et al., 2023), 32 (Collins, 2022b) face stimuli, 33 (John-Saaltink et al., 2016), 34 (Sheehan & Serences, 2022), 35 (Gekas et al., 2019). Study numbers are more clearly visible in the electronic version of the document. (**B**) We computed serial dependence strength as a function of time across intervening n-back trials (x-axis). For each data point in each study, we computed the average trial time. The solid black line is the a best fitting clipped-line fit. The ribbons are 95% confidence interval. Serial dependence strength gradually decayed with increasing time. Studies 1–22 are same as A, with 23 (Manassi & Whitney, 2022), 23 (Bliss et al., 2017), and 24 (Collins, 2022b) face stimuli. (C–D) Subplots of data plotted in A for orientation perception (**C**) and face perception (**D**).

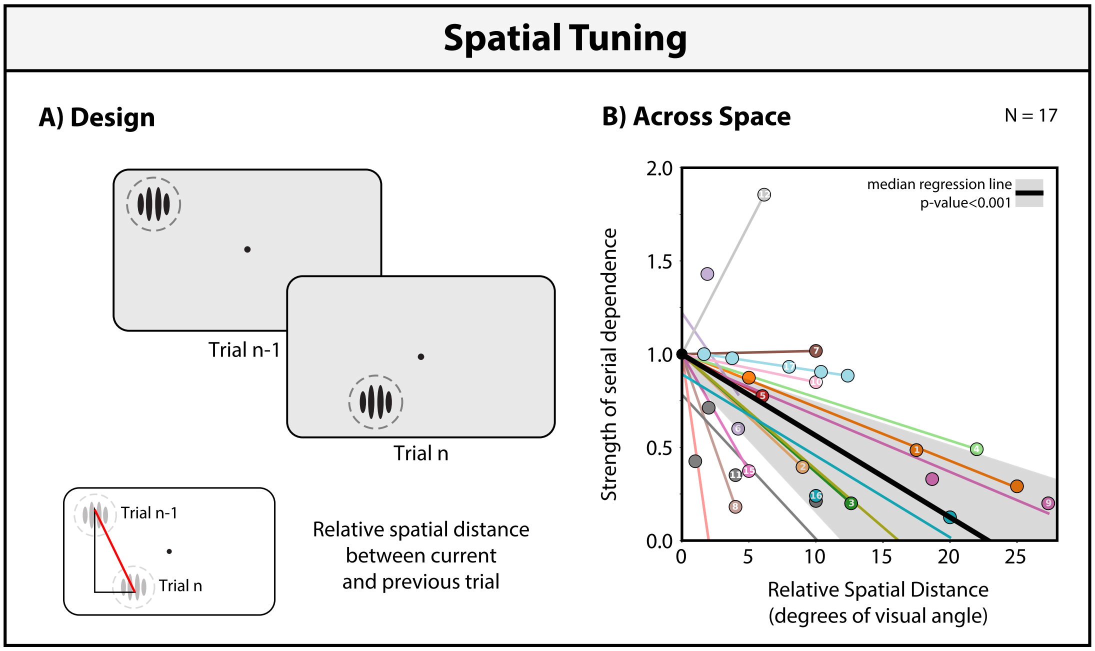

Figure 7. Spatial tuning of serial dependence. (**A**) In a typical serial dependence experiment, the location of the stimulus (e.g., an oriented Gabor) is randomized on each trial. Serial dependence strength is then measured as a function of the relative spatial distance across trials. (**B**) We computed serial dependence strength as a function of the relative spatial distance between current and 1-back stimuli (x-axis). Y-axis shows the strength of serial dependence; we normalized the strength of serial dependence dividing by the smallest relative spatial distance condition of each study. For each study ($N = 17$, across different visual stimuli), we computed the predicted regression line across relative spatial distance. The black line shows the median bootstrapped regression line. Shaded grey error bars indicate 95% Confidence Interval across studies. Serial dependence spreads beyond the location of the stimulus itself, with a half amplitude of serial dependence extending beyond 10°. Serial dependence is therefore broadly tuned to spatial location, but it does not extend everywhere in the visual field. Reviewed studies are 1 (Fischer & Whitney, 2014), 2 (Fornaciai & Park, 2018b), 3 (Manassi et al., 2019), 4 (Collins, 2019), 5 (Collins, 2022b), 6 (Manassi et al., 2021), 7 (Fritsche et al., 2017), 8 (Collins, 2022a), 9 (Liberman et al., 2016), 10 (Corbett et al., 2011), 11 (Golomb et al., 2014), 12 (Galluzzi et al., 2022), 13 (Fischer et al., 2020), 14 (John-Saaltink et al., 2016), 15 (Zeljko & Grove, 2021), 16 (Kondo et al., 2022), 17 (Luo et al., 2022). Individual numbers are more clearly visible in the electronic version of the document. Not shown in the graph for space reasons: 13 (−0.23 on y coordinate) and 14 (−4 on y coordinate).

reduces measured serial dependence, suggesting a form of spatial tuning. This manipulation is most common in studies on serial dependence of orientation perception. It is a far less common independent variable in object recognition studies (Starks, Shafer-Skelton, Paradiso, Martinez, & Golomb, 2020).

Figure 7 shows the spatial tuning of orientation serial dependence for a group of 17 studies. The spatial tuning is significant, with a half width of over 10° visual angle. The vast majority of studies report spatial tuning ($X^2 = 9.9$, $p < 0.01$), with a couple of outliers, including Fritsche et al. (2017), who found no spatial tuning, and Galluzzi et al. (2022) who found reversed spatial tuning (each $Z > 1.7$ from the mean). These outliers were not excluded from the meta-analysis.

The spatial dimension in this meta-analysis (Figure 7) is relative location. But, it is worth highlighting that in most studies of serial dependence, spatial manipulations confound retinal-, head-, body-, screen-, and world-centered coordinates. There are a few exceptions to this (Cicchini, Mikellidou, & Burr, 2017; Collins, 2019; Fischer & Whitney, 2014; Mikellidou, Cicchini, & Burr, 2021) that have dissociated one or more of these dimensions. From a meta-analytic standpoint, more studies are needed to compare and dissociate serial dependence that might occur in different coordinate frames. In any case, this meta-analysis provides strong evidence for serial dependence as a spatially tuned visual phenomenon, but whether it occurs in *more* than one spatial dimension remains an open question. It is at least plausible.

Additional evidence for spatial tuning comes from studies that found serial dependence in position perception (Barbosa et al., 2020; Bliss et al., 2017; Manassi et al., 2018a; Papadimitriou et al., 2015): nearby sequential stimuli are judged to be closer together than they actually are. The fact that serial dependence in this domain occurs only for nearby sequential stimuli, but not for distantly separated ones, may be considered a kind of spatial selectivity. Further evidence comes from studies which implemented simultaneous judgements (2AFC) with a previously presented stimulus as inducer (Cicchini et al., 2017; Fischer & Whitney, 2014; Fornaciai & Park, 2018b; Fritsche et al., 2017; John-Saaltink, Kok, Lau, & De Lange, 2016; e.g., Figures 4A and 4B); in this design, serial dependence can occur only if the inducer biases the probe more than the spatially separated reference stimulus.

Unfortunately, there are few studies that have measured the spatial tuning of serial dependence in domains other than orientation perception. An article by Corbett et al. (2011) reported that serial dependence in numerosity perception is spatially (visual field) specific; articles by Stark et al. (2020) and Collins (2022b) found that serial dependence in face judgments is spatially specific; an article by Manassi et al (2019) found that serial dependence in shape perception is spatially tuned; serial dependence in variance led to conflicting findings (Suárez-Pinilla et al., 2018). Most articles on the spatial selectivity of serial dependence, though, are in the orientation domain. This is an important limitation because spatial tuning is clearly a defining feature of orientation serial dependence. Whether it holds in a substantially similar manner for faces, objects, colors (e.g., Figure 1), or the several separable dimensions of faces (e.g., Figure 3C) is unclear, but it is a valuable question for future research.

Properties of serial dependence: Feature tuning

Serial dependence is often found to nonlinearly depend on the similarity with the prior stimulus. Figures 8A–C shows an example of this in the orientation domain. When sequential stimuli are similar, there is a stronger serial dependence effect, resulting in an inflection point on the DoG function and stronger bias near 0 on the X axis (Figures 8A and 8B and Figure 2B). For sufficiently different stimuli (x-axis locations far from 0), no serial dependence occurs.

Figure 8C shows a meta-analysis of feature tuning in several domains. Feature tuning here is operationally defined by measuring half the peak-to-trough distance of the running average (i.e., half-width in Figure 8B) as a proportion of the total stimulus range. We adopted this measure because different kinds of stimuli have different ranges and units; moreover, some stimulus distributions are prothetic (e.g., linear like size or number), and some are metathetic continua (circular, like orientation). In each domain, our meta-analysis revealed a significant feature tuning, with half-width distances that are approximately 25% of the full stimulus range. Overall, there seems to be a general consistency in the stimulus similarity tuning, but whether there are underlying differences in the tuning width for different dimensions remains an open question, as the number of studies is still limited.

Serial dependence is not always reported to be feature-tuned. Sometimes, there is a simple linear dependence of the current perceptual judgment on the previous stimulus. This is most often found for prothetic dimensions like numerosity or visual variance, especially where discriminability is coarse (Suárez-Pinilla et al., 2018; Xia et al., 2016). Studies showing that serial dependence is only linearly dependent on the stimulus space could be due to a variety of factors, including the range of the stimulus dimension, or the limited discriminability of the sequential stimuli. For example, within any sufficiently narrow range of tested stimuli, even orientation serial dependence seems to be linear. Reinforcing this idea, Figure 8D shows feature tuning reported in studies of serial dependence in face recognition. In the studies that reported feature tuning—stronger serial dependence for sequentially similar things—the overall serial dependence effect sizes were also larger (Figure 8E; blue bar vs gray bar). This could indicate that feature tuning occurs primarily in domains like face identity, which has a stronger baseline serial dependence (Figure 3C). Consequently, finding tuning in attractiveness judgments might be difficult not because it is absent but because the effect size is so small to start with and measuring a second-order modulation of that requires a lot of power.

In addition to the primary tuning of serial dependence to feature-distance, it is worth mentioning that some publications also report the existence of "peripheral bumps" (Bliss et al., 2017; Fritsche et al., 2017) (i.e.; repulsive biases when consecutive stimuli are *far* apart). However, the consistency of these effects remains unclear: they are sometimes reported in the orientation domain, though mostly in analyses of collapsed or pooled data (Ceylan & Pascucci, 2023; Fritsche et al., 2017; Samaha et al., 2019; van Bergen & Jehee, 2019), and they are often absent or inconsistent (Collins, 2019; Gallagher & Benton, 2022; Kondo, Murai, & Whitney, 2022; Lau & Maus, 2019; Liberman et al., 2014; Sheehan & Serences, 2022; Teng, Fulvio, Jiang, & Postle, 2022). In non-orientation domains, the peripheral bumps are even less consistent. For example, they were found in some studies (Barbosa et al., 2020; Bliss et al., 2017) but not in others (Papadimitriou et al., 2015; Papadimitriou, White, & Snyder, 2017), and these negative "bumps" are not found for shape perception (Manassi et al., 2019; Manassi et al., 2021) or face recognition (Collins, 2022b; Liberman et al., 2014; Liberman et al., 2018). There is, therefore, not enough consistency across studies for a coherent meta-analysis of these peripheral bump effects. Future research is needed to evaluate whether these biases are genuine forms of repulsion, whether they occur independent from artifacts, whether they hold only in the orientation

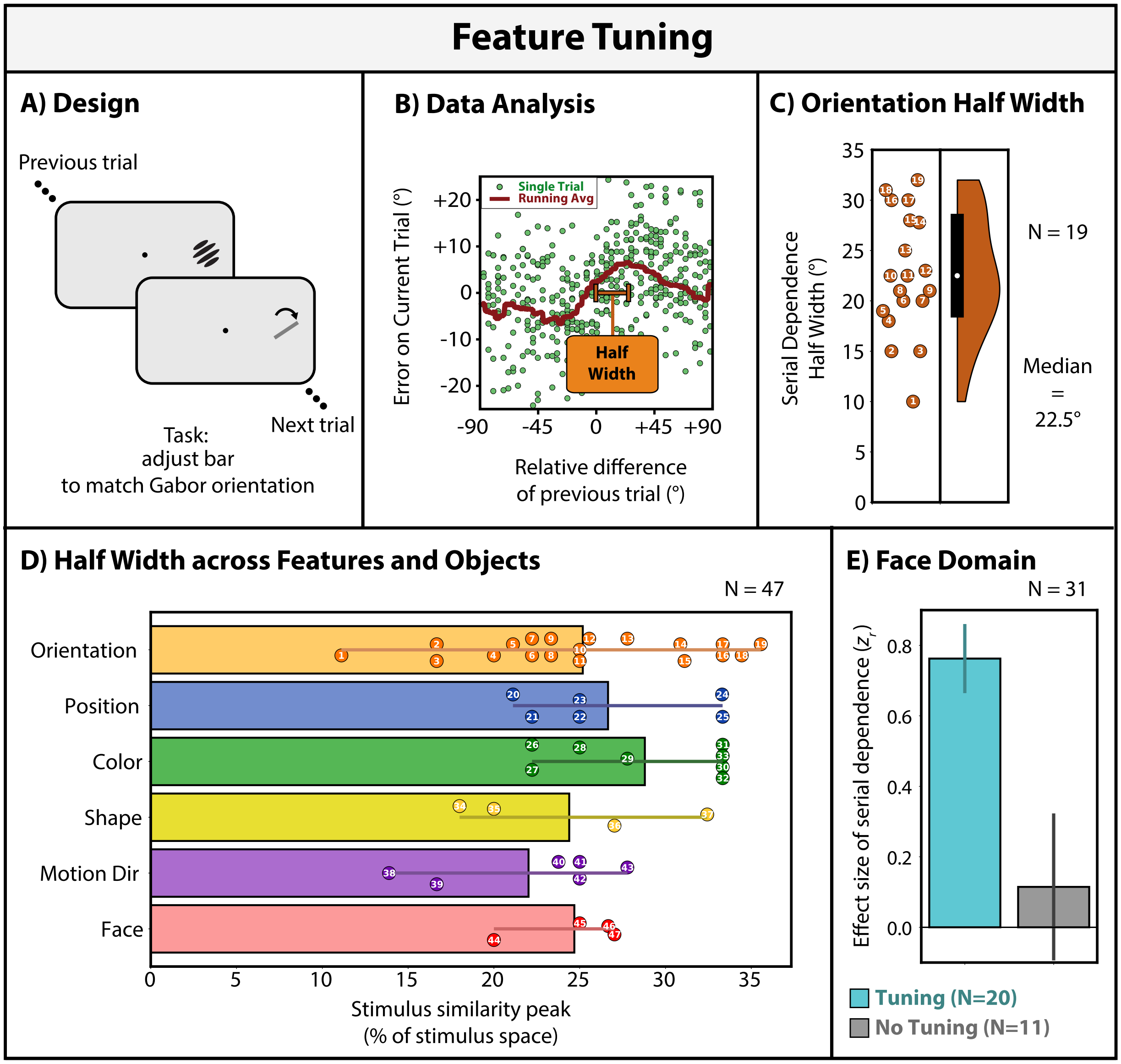

Figure 8. Feature tuning of serial dependence. (**A**) In a typical orientation serial dependence experiment, observers are presented with a sequence of randomly oriented Gabor patches, and they are asked to adjust a bar to match the orientation of the Gabor on each trial. (**B**) Errors in orientation judgments are plotted relative to the difference between sequential stimulus orientation, yielding a characteristic derivative-of-Gaussian shape. Serial dependence (as shown by the red running average line) occurs predominantly for relatively similar orientations (peak around 25°), but not for dissimilar ones. This feature tuning can be quantified by computing the absolute value of peak distance in the running average of the raw data (red line). (**C**) Half-width of serial dependence in orientation perception ($N = 16$). The half violin plot indicates the median (white circle), interquartile ranges (black rectangles) and the density distribution (orange shape). Study numbers are consistent with the following panel. (**D**) Feature tuning of serial dependence in several different domains. The half-width of serial dependence is divided by the full stimulus range in each respective study. This measures the proportion of the stimulus range within which serial dependence is strongest. For example, a study that reported a linear effect (no feature similarity tuning) would have a value of 100% on the abscissa. The data in panel B, on the other hand, would have a value of ~30% on the abscissa. Each colored bar indicates the mean bootstrapped stimulus similarity peak across different individual studies (dots). A total of 43 studies were analyzed, broken down into separate stimulus types (orientation, position, color, shape, motion, faces). Serial dependence strength was highest when sequential stimuli were within ~20% to 30% of the full stimulus range. Reviewed studies in panels C and D are Orientation: 1 (Ceylan et al., 2021), 2 (Cicchini et al., 2021), 3 (Pascucci et al., 2019), 4 (Liberman et al., 2016), 5 (Galluzzi et al., 2022), 6 (Samaha et al., 2019), 7(M. Luo et al., 2022), 8 (Kondo et al., 2022), 9 (Gallagher & Benton, 2022), 10 (Collins, 2019), 11 (Fritsche et al., 2017),12 (Shan & Postle, 2022), 13 (Sheehan & Serences, 2022), 14 (Fischer & Whitney, 2014), 15 (Pascucci & Plomp, 2021), 16 (Manassi et al., 2017), 17 (Lau & Maus, 2019), 18 (van Bergen & Jehee, 2019), 19 (Teng et al., 2022); Position: 20 (Manassi et al., 2018a), 21 (Bliss et al., 2017), 22 (Barbosa et al., 2020),

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23 (Stein et al., 2020), 24 (Papadimitriou et al., 2015), 25 (Papadimitriou et al., 2017); Color: 26-27 (Van den Berg et al., 2012), 28 (Bays et al., 2009), 29 (Souza et al., 2014), 30 (Shafto et al., 2014), 31 (Souza et al., 2014), 32-33 (Foster et al., 2017); Shape: 34 (Collins, 2022a), 35 (Collins, 2022b), 36 (Manassi et al., 2019), 37 (Manassi et al., 2021); Motion direction: 38 (Czoschke et al., 2019), 39 (Fischer et al., 2020), 40 (Moon et al., 2023) (motion clouds), 41 (Alais et al., 2017), 42 (Bae & Luck, 2020), 43 (Moon et al., 2023) (dot motion); Face: 44 (Collins, 2022b), 45 (Yu & Ying, 2021), 46 (Liberman et al., 2018), 47 (Liberman et al., 2014). Study numbers are clearly visible in the electronic version of the document. **E**) Studies that reported feature tuning ($N = 20$) in face serial dependence had a stronger effect size overall compared to the studies that did not report feature similarity tuning ($N = 11$).

domain, and whether they are consistent within and across observers.

Properties of serial dependence: Attention tuning

Several studies have reported that attention modulates or even mediates serial dependence (Fischer & Whitney, 2014; Fritsche & de Lange, 2019; Kim et al., 2020), at least in the orientation domain. A few studies have reported that serial dependence can occur passively (Goettker & Stewart, 2022) or for task-irrelevant features (Fornaciai & Park, 2018a), blurring the role of attention. Using a simple but conservative $X^2(1)$ proportion test, with study as a random effect, we found that fewer attentional resources caused a reduction in serial dependence ($N = 8$, $X^2(1) = 4.5$, $p < 0.05$; Figure 9). The only exception was a study where the opposite trend was reported (Collins, 2022a), but there was no significant difference between cued and uncued conditions. Taken together, these results show that serial dependence decreases with decreasing attentional resources devoted to previously experienced stimuli. Although this does suggest an important role of attention, it does not mean that attention always

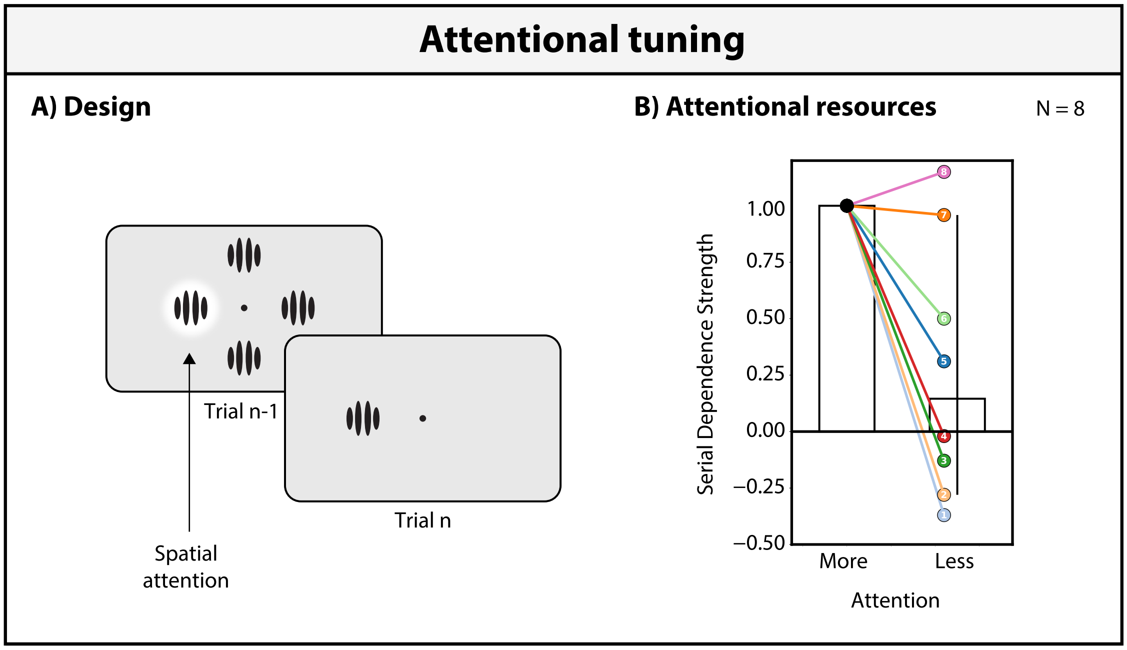

Figure 9. Attention tuning of serial dependence. (**A**) In a typical experiment to investigate the role of attention in serial dependence, observers are presented with a group of Gabors organized in a ring around the fixation point, and are cued to attend to one of the Gabors before stimulus onset. Serial dependence is stronger from the cued Gabor (white blur) compared to the non-cued ones. (**B**) Modulation of serial dependence with attention. The magnitude of serial dependence was normalized within each study. For the purposes of the meta-analysis, conditions were grouped and classified in a binary manner, reflecting relatively more or less (spatial or feature) attention. Bars indicate bootstrapped median across studies. Overall, there is a significant modulation of serial dependence with attention: more spatial or feature attention devoted to the task tends to increase measured serial dependence. Of these eight studies, six were in the orientation domain. Interestingly, the studies that reported the smallest modulation by attention were in perceived numerosity (7) and face (8). It is possible that different stimulus dimensions rely on attention in different ways. Included studies are 1 (Fischer & Whitney, 2014), 2 (Rafiei et al., 2021b), 3 (Rafiei et al., 2021a), 4 (Kim et al., 2020), 5 (Fritsche & de Lange, 2019), 6 (Liberman et al., 2016), 7 (Fornaciai & Park, 2018b), 8 (Collins, 2022a).

matters in every instance of serial dependence or in every domain; it may be that different stimuli or tasks rely on attention to different degrees. Indeed, most studies that have controlled and manipulated attention did so for serial dependence in orientation perception. It may also be the case, as some have hypothesized, that serial dependence could operate at many stages of visual processing (Kiyonaga et al., 2017; Liberman et al., 2014; Manassi et al., 2018a); accordingly, some of these stages (Collins, 2022a; Goettker & Stewart, 2022) may rely less on attention compared to other stages like face processing.

Beyond attention, several studies have highlighted that serial dependence is modulated by high-level factors such as awareness (Fornaciai & Park, 2019a; Kim et al., 2020), memory (Bliss et al., 2017; Fritsche et al., 2017; Mei, Chen, & Dong, 2019; Shan & Postle, 2022), task (Fischer et al., 2020; Togoli, Fedele, Fornaciai, & Bueti, 2021), confidence (Abreo, Gergen, Gupta, & Samaha, 2023; Bosch, Fritsche, Ehinger, & de Lange, 2020; Samaha et al., 2019), and decision (Pascucci et al., 2019). For example, many experiments have reported an effect of memory on serial dependence, such that increasing memory requirements increases the measured serial dependence effect (Barbosa et al., 2020; Bliss et al., 2017; Fritsche et al., 2017; Mei et al., 2019; Togoli et al., 2021). However, it has proven very difficult to isolate conceptually and methodologically the contribution of these high-level factors (e.g. task vs attention, memory vs decision, etc.). There is an unavoidable ambiguity and imprecision in what counts as "perception," "decision," "awareness," and "memory," and the field has not agreed upon operational definitions for these terms. In addition, studies that manipulate working memory requirements often do so in idiosyncratic ways, for example by lengthening the retention or inter-trial-interval, or extending the mask duration, or changing some other temporal property of the design. Unfortunately, the substantial differences in methods precludes performing a meta-analysis for parametric changes in serial dependence as a function of something like delay. Like the attention-tuning effect (Figure 9), it is very important caveat to keep in mind that finding a memory-modulation does not indicate that implicit/explicit memory is always involved or a necessary component of all serial dependence effects. Moreover, the working memory delay effect needs to be reconciled with the presence of temporal tuning found in many studies (Figure 6).

The role of individual differences

Serial dependencies, like other visual phenomena, are characterized by significant individual differences (Van Geert, Moors, Haaf, & Wagemans, 2022). Several specific papers have reported this in both orientation perception (Figures 10A–B) and in face perception (e.g., Figure 10C). Figure 10D is a summary of the studies that have reported individual observer data in orientation serial dependence, totaling nearly 300 individual observers. The visualization shows the proportion of observers in each study that displayed serial dependence (a positive perceptual pull toward the previous stimulus orientation; gray values indicate negative aftereffect or repulsion). Overall, there is a highly significant proportion of single observers who exhibit positive serial dependence in perceived orientation ($X^2(1) = 87, p < 0.0001$). As highlighted in Figures 10A and 10B, several studies report finding individual observers who do not show positive serial dependence and instead display a negative aftereffect (gray regions in Figure 10D). Across the ∼300 single observers whose individual data was reported (including Figures 10A–B), approximately 23% of the tested participants displayed this negative aftereffect (rather than positive serial dependence). Whether this is simply due to noise and lack of power remains unclear. Subdividing these studies into those that presented foveal stimuli (less uncertainty) and peripheral stimuli (more uncertainty) suggests that there is a difference in the proportion of observers who display positive serial dependence for foveal (70%) versus peripheral (83%) stimuli, meaning that foveal stimuli produce more negative aftereffects and reduce the measured serial dependence effect. This does not undermine the meta-analyses of population level effects in Figure 10, but, importantly, it hints at the variability that could exist in the population of individual participants, and the importance of measuring individual observers over time to assess reliability of the individual differences (Goodhew & Edwards, 2019; Van Geert et al., 2022).

The fact that not every single observer shows (or seems to show) positive serial dependence in every experimental session highlights several important considerations. First, the field needs more studies that report single observer data (in the tradition of vision science), with larger trial count (cf., Figure 2D), and with larger sample sizes. Collapsing or pooling across observers into a single super-subject has become a popular practice to overcome limited numbers of trials, but it masks individual differences, waters down the measured effects, and likely underestimates effect sizes (in both directions). Second, we need more studies that report test-retest reliability within observers (Kondo et al., 2022), to get a better estimate of the noise ceiling. Third, we believe the field should explore more efficient approaches to measuring serial dependence that require fewer trials per observer, such as slope of the central line rather than the full DoG function, more efficient stimulus distributions, or other approaches (Cicchini et al., 2017; Cicchini et al., 2018; Manassi & Whitney, 2022). Fourth, the reliability of positive serial dependence is well-established (e.g., Figures 2–3):

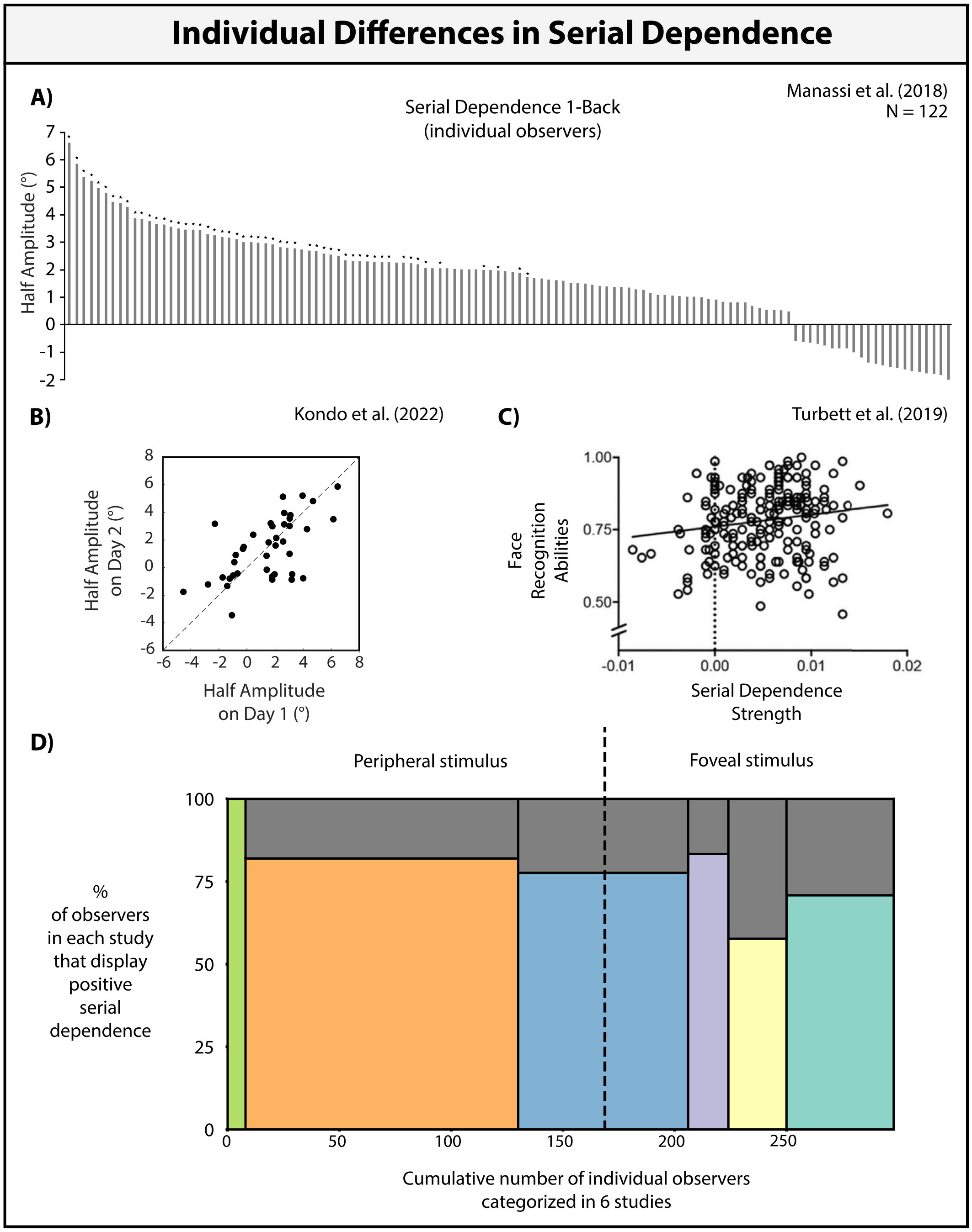

Figure 10. Individual Differences in Serial Dependence. (**A**) Individual differences in serial dependence have only been measured in a few studies. These include orientation serial dependence (**A**–**B**) and face recognition (C). Importantly, however, simply finding that individual observers vary in measures of serial dependence is not sufficient to demonstrate individual differences, without an estimate of the reliability (Goodhew & Edwards, 2019). Instead, some measure of stability, test-retest reliability (e.g., Kondo et al., 2022, panel B), or association with other variables (panel C) is required to draw stronger conclusions about the presence and nature of individual difference. (**C**) For example, Turbett et al. (2019), demonstrated that individual differences in face recognition ability is associated with the magnitude of serial dependence. (**D**) Prevalence of positive serial dependence reported in individual observers across six studies that reported individual observer data. Each colored column region represents one study that reported single observer serial dependence effects like that shown in Figure 1B. The width of each colored region represents the relative number of participants in each study, with the cumulative total number of individual participants on the abscissa. The gray regions above each colored column represent the proportion of observers in each respective study who displayed negative aftereffect (a repulsion, rather than an assimilation, toward previously experienced stimuli). The proportion of observers who show positive serial dependence in perceived orientation (sum of colored regions/sum of gray regions) is ~77%, $X^2(1) = 87$, $p < 0.0001$. The six studies are, from left to right: green (Fischer & Whitney, 2014); orange (Manassi, Murai, & Whitney, 2018b); blue (Kondo et al., 2022) foveal and peripheral

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stimuli; purple (Samaha et al., 2019); yellow (Zhang & Alais, 2020); pearl aqua (Pascucci et al., 2023). The vertical dashed line separates studies that had either foveal or peripheral stimuli (Kondo et al., 2022 had both peripheral and foveal conditions).

there is significant positive serial dependence, and there are stable individual differences (Kondo et al., 2022). Whether this holds for the ∼23% of observers who show repulsive aftereffects—whether these repulsive effects are actually stable—is far less clear and has yet to be demonstrated. Finally, a gaping hole in the literature is that there are no studies comparing individual differences across different stimulus dimensions. Many have suggested that serial dependence operates at multiple levels of processing (Kiyonaga et al., 2017; Liberman et al., 2014; Manassi et al., 2018a), and, accordingly, we would expect individual differences in serial dependence may not correlate as highly across stimulus dimensions. That is, observers who display strong serial dependence in face perception may not show strong serial dependence in orientation perception. A range of additonal questions are presented in Box 1.

Box 1. Future directions and outstanding questions prompted by the meta-analysis

Is serial dependence implemented at each level of visual processing? The meta-analysis shows serial dependence exists for many different kinds of stimuli, but is it implemented at each level of processing? The meta-analysis suggests some perceptual judgments have less serial dependence, such as face attractiveness (Figure 3). Perhaps different visual stimuli and functions have different degrees of serial dependence, and perhaps they can be dissociated (Liberman et al., 2014; Manassi et al., 2018a; Pascucci et al., 2023). Individual differences may be a way to address this (Zhang & Whitney, 2017).

Is the spatial and temporal tuning of serial dependence different for different features and objects? It may be possible to dissociate different forms or levels of serial dependence by comparing their tuning properties.

Is there a systemic relation between the spatial and temporal tuning of serial dependence? Is it a spatiotemporal serial dependence or are they separable dimensions that do not necessarily co-vary? Individual differences may be a way to address this, as well.

Does serial dependence occur in other domains beyond basic vision? Is there serial dependence in social cognition, in behavioral economics, in emotion and cognitive control? What are the connections between serial dependence and heuristics and biases reported in that literature? For example, there are anchoring effects and other sequential biases in economic decisions, but those are not known to have clear tuning properties like serial dependence. On the other hand, whether they are tuned like serial dependence has not really been tested.

Where in the brain is serial dependence implemented for any given visual feature or object? There are several reports of neural signatures of serial dependence, but very mixed results with precious few studies that have linked trial-wise serial dependence behavioral measures with any consistent neural correlate of the effect. Something in the brain must implement serial dependence, echoing its tuning properties revealed in the meta-analysis here, but what is the signal? Does it differ for different stimuli? Is it silent, or multiplexed, or sustained, or in oscillations, or in spontaneous activity, or in non-neural activity, or something else?

Does serial dependence echo the temporal statistics of features, objects, and high-level properties of scenes? It is possible, if not likely, that different kinds of visual information are characterized by different temporal statistics in the natural world. For example, orientation, color, surface, shape, face identity, and emotional content in scenes might have very different autocorrelation functions in typical observer experience. These might also depend on the particular environment, age, culture, development, and other factors. Are the putative differences in the temporal statistics of different kinds of information associated with differences in serial dependence?

How do individual differences impact serial dependence at the observer level? The temporal statistics (e.g., autocorrelation) of orientation information in natural movies have been reported before (van Bergen & Jehee, 2019), but not at the individual observer level. The temporal statistics of emotion information in natural movies was also reported before (Ortega et al., 2023), but these were not linked to individual observers either. Is it possible that the temporal statistics of visual information at any level is dictated in part by how humans as individuals interact and move around the world? Do the goals and limits of particular observers, and their interactions with the world, shape the temporal statistics of incoming information in a way that mimics or predicts individual differences in serial dependence?

Do individual differences in serial dependence arise from differences in age, visual impairments, expertise, atypical development, or other idiosyncratic characteristics? Whether there are differences in serial dependence that echo other individual differences is a very broad, open question. Group level analyses with pooled data are inadequate to tackle this question. More studies at the individual observer level and on individual differences are needed (Kondo et al., 2022; Turbett et al., 2021; Van Geert et al., 2022).

Does perceptual learning impact serial dependence? Serial dependence could be a fast-adapting or a slow-adapting process. Although it is possible, it is not necessarily the case that serial dependence must reflect the temporal statistics of the world in a rigid and fixed way, independent of the particular observer; the needs and interactions of individual observers could modulate the incoming and learned temporal statistics. Therefore serial dependence could change over time, depending on modulations of the incoming information and the goals/needs of the observer. Perceptual learning experiments combined with measures of serial dependence at the individual observer level could help address this.

What is the development of serial dependence and does it vary with observer age? Is there serial dependence in infant object recognition, for example measured in preferential looking experiments? Or are infants with less exposure to the temporal statistics of natural scenes less susceptible to serial dependence effects? Does serial dependence of different kinds of information develop at different rates? Does serial dependence in development echo the changes in perceptual sensitivity, efficiency, and stability?

What is the role of attention in different forms of serial dependence? Attention matters for orientation serial dependence (Figure 9), but whether it matters in other forms of serial dependence is not clear because there are not yet enough studies on it.

Can serial dependence be trained away? Can the visual system actually learn randomness? Statistical learning exists (Fiser & Lengyel, 2022) but whether this learning is associated with specific trial-by-trial biases (serial dependencies) is less clear. At a broader level, is randomness a fundamental dimension of perception and is it related to serial dependence?

Why might the feature tuning of serial dependence vary across individuals and across stimuli? The meta-analysis here reveals that serial dependence is most often tuned to stimulus similarity. The width of that tuning doesn't seem to substantially differ across stimulus type, but it could; there aren't enough studies yet to know. More importantly, the tuning width may vary across different observers, as well, but these have rarely been tested or reported (Turbett et al., 2019) and the test-retest reliability of these individual differences remains unclear. If there are stimulus and observer individual differences, why do these occur and what do they reflect?

What is the role of internal and external noise in serial dependence? The role of noise in serial dependence has been studied in some forms, but the manipulations yield mixed results. There are both external and internal sources of noise, however, and it is worth considering what counts as noise for different stimuli and tasks (beyond, for example, 1/f noise), and what the visual system attributes the noise to. Future studies could take advantage of equivalent noise paradigms to try to parcel out the impact of different forms of noise in sequences.

Does serial dependence occur for nested properties of compound objects? Some similar ideas have been explored before (Collins, 2022b; Fischer et al., 2020; Liberman et al., 2018; Pascucci et al., 2023; Taubert et al., 2016a), but only with features. Complex scenes are made of compound objects that are themselves made up of attentionally segmentable features and parts (e.g., an emotional scene has an expressive face, which has a salient set of face parts made up of features like color, orientation, etc.) We can attend to any of these levels of analysis (color, nose or mouth orientation, configuration of eyes-nose-mouth, holistic properties of the face identity, expression information, contextual scene information, or interactions between these). Does serial dependence happen only at the attended level of analysis? Or at all levels?

How do serial dependencies relate to (working) memory? Which forms of serial dependence involve memory and how? Is (maladaptive) proactive interference dissociable from (adaptive) serial dependence, or is it actually a form of serial dependence? Are individual differences in memory related to individual differences in serial dependence? Does this hold within and across different features and objects?

How is serial dependence related to ongoing narratives of perceptual consciousness? Are serial dependencies consistent with theories of consciousness (Seth & Bayne, 2022) like global workspace theory, multiple drafts model, re-entry and predictive processing theories, integrated information theory, and other accounts of awareness?

What are the computational goals and functional benefits of serial dependence? Several studies have reported putative computational goals of serial dependence including improved efficiency, accuracy, and stability. Relating these benefits specifically to individual differences in perception and expertise would further test these ideas. In the face domain, this work has started (Turbett et al., 2019), but more is needed in other areas of perception science, including tying the domain specific functional benefits to the spatial and temporal tuning properties of serial dependence.

Does serial dependence vary in atypical populations? For example, in neurocognitive developmental disorders such as those with autism? Or those with schizophrenia? Those with depressive and anxiety disorders? Those with other forms of mental illness? Intriguing recent work has begun to explore this (Stein et al., 2020), but there is not enough published yet to conduct a meta-analysis, and the existing literature is mixed. Higher-powered studies are required, as are studies using stimuli beyond just orientation. The meta-analysis here demonstrates that face identity serial dependence is significantly stronger than face attractiveness serial dependence, casting doubts on the (often implicit) assumption that one form of serial dependence (e.g., orientation) can be used as a proxy for other forms of serial dependence.

Can serial dependence be modulated with transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (tDCS)? If so, can it be done in a stimulus-specific or location specific manner? The meta-analysis reveals a very precise picture of the tuning properties of serial dependence, which provides a firmer foundation for testing manipulations of serial dependence with noninvasive techniques such as TMS.

This laundry list of questions and future directions only scratches the surface. It does, however, highlight the value of the meta-analyses, which revealed the diagnostic properties of serial dependence and provide a baseline of comparison for future (and past) work.

Discussion

The meta-analyses here firmly establish serial dependence in orientation (Figure 2), face (Figure 3), and numerosity perception (Figure 4). Importantly, our meta-analyses suggest that there are four primary dimensions of serial dependence: temporal tuning (Figure 6), spatial tuning (Figure 7), feature tuning (Figure 8), and attention-tuning (Figure 9). Although there could be others that remain to be isolated or replicated sufficiently, these four reveal the core of an operational definition of serial dependence. They show that serial dependence is a quantifiable and classifiable family of phenomena. They do not indicate that serial dependence is a unitary, singular, or modular construct, nor do the meta-analyses show that there is only one type of spatial or temporal tuning that holds across all features and objects. It is important to mention that each of the tuning properties we have considered do not represent rigid, hardwired, single mechanisms which act in isolation, but instead they continuously modulate each other and can be modulated depending on stimuli, task, context, low or high level factors (Ceylan & Pascucci, 2023). Instead, we propose that our meta-analyses capture the general diagnostic criteria for what counts as serial dependence. Past and future studies that are presumed or thought to investigate serial dependence (as opposed to other phenomena) need to be considered in light of these criteria.

Temporal tuning

One of the diagnostic criteria of serial dependence is that it is temporally tuned (Figure 6). The temporal tuning may differ for different stimuli, but for orientation it ranges between ∼12 to 20 seconds. It seems likely that intervening information modulates the temporal tuning, as well, but even in the absence of intervening stimuli there seems to be some fading of the effect. Importantly, the temporal tuning might vary as a function of the stimulus or level of visual analysis. For example, comparing orientation serial dependence (Figure 2) to face (Figure 3) or numerosity serial dependence (Figure 4) might reveal differences in the time constant of the temporal tuning. However, there are too few studies, and the methods differ more between stimuli than within stimuli, limiting broad generalizations other than the fact that serial dependence is temporally tuned. Once additional studies are published on temporal tuning in different domains, this will allow a future meta-analysis to distinguish between stimulus classes.

Spatial tuning

The spatial tuning of serial dependence is striking (Figure 7). The studies we reviewed very consistently show a decrease of serial dependence with increasing relative spatial distance. This kind of tuning is much broader than what was reported for negative aftereffects (Boi, Oğmen, & Herzog, 2011; Knapen, Rolfs, & Cavanagh, 2009; Knapen, Rolfs, Wexler, & Cavanagh, 2010), a fact that alone suggests a distinction in the underlying mechanism of serial dependence. However, the spatial kernel of serial dependence is not infinite—it does not spread everywhere (Figure 7).

The dissociation between the relatively broad spatial tuning for serial dependence and the much narrower spatial tuning for most negative aftereffects (Boi et al., 2011; Knapen et al., 2009; Knapen et al., 2010) may help explain the outlier studies in Figure 7. If both adaptation (negative aftereffects) and positive serial dependence occur at the same time, but with differences in spatial selectivity, then there can be a seeming (artifactual) lack of spatial tuning in serial dependence (Fritsche et al., 2017), and possibly even an increase in the effect with separation (Galluzzi et al., 2022). For instance, when measuring serial dependence at two distinct locations (e.g., same vs different location), attractive and repulsive effects may cancel each other at the same location (i.e., local tuning), with serial dependence emerging for different locations (i.e., broad tuning), thus giving the false impression of no tuning in the first place.

Serial dependence is undoubtedly spatially tuned (Figure 7), but the coordinate frame(s) of that tuning is still somewhat unclear. There is ample evidence for an effect in at least eye-centered (retinotopic) coordinates (Collins, 2019; Fischer & Whitney, 2014), but this does not preclude the possibility of serial dependence in other or additional coordinate frames as well (Mikellidou et al., 2021). This might be expected if serial dependence occurs at multiple stages in cortical processing. Unfortunately, there are not yet enough studies to perform a meta-analysis on serial dependence in distinct coordinate frames, but there is a hint that it may operate in spatiotopic coordinates, at least to some degree (Cicchini et al., 2017; Fischer & Whitney, 2014; Mikellidou et al., 2021). Alternatively, the very broad retinotopic tuning (Fischer & Whitney, 2014; Collins, 2019) could, in virtue of its breadth, give serial dependence a quasi-spatiotopic tuning without an explicit coordinate transformation.

Feature tuning

Serial dependence occurs with sufficiently similar sequential features and objects but not dissimilar ones (Figure 8). Intriguingly, it seems as if the stimulus-similarity tuning is constant across features and objects (Figure 8C), but research on this issue is far from conclusive. It may be argued that feature tuning of serial dependence in face perception is not often present, but (1) absence of proof (or absence of report in the study) should not be considered as proof of absence, (2) studies that do not mention or find feature tuning are often characterized by a smaller effect size (Figure 8D), and (3) such null results could be due to methodological issues (face stimuli were too dissimilar, the range of dissimilarity was not fully tested, etc.). Despite these sorts of concerns, the meta-analysis provides concrete evidence that feature-tuning of serial dependence is the norm.

Attentional tuning

Attentional resources devoted to previous stimuli determine the strength of serial dependence (Figure 9). More particularly, endogenous spatial attention (Fischer & Whitney, 2014) and feature-based attention (Fritsche & de Lange, 2019) were found to play a crucial role. The exact mechanism between serial dependence and attention is still unclear; some studies found that less attentional resources modulate serial dependence (Fornaciai & Park, 2018b; Fritsche & de Lange, 2019; Liberman, Zhang, & Whitney, 2016), erase it (Kim et al., 2020) or lead to the opposite bias (i.e. negative aftereffect) (Fischer & Whitney, 2014; Kim et al., 2020; Rafiei, Chetverikov, Hansmann-Roth, & Kristjánsson, 2021a; Rafiei et al., 2021a). Importantly, there is evidence that some types of serial dependence can also occur for task-irrelevant features (Collins, 2022a; Fornaciai & Park, 2018a; Goettker & Stewart, 2022; Manassi & Whitney, 2022), thus making it unclear whether attention is a strict requirement for serial dependence to occur or if its role is selective for stimulus type and task. Future research will need to fully characterize the role of specific types of attention (Carrasco, 2011) with specific stimulus classes, independently of confounding factors such as task, decision, and memory.

The primary tuning properties of serial dependence revealed in the meta-analyses can be useful to understand the actual nature of serial dependence. On one hand, serial dependence cannot be considered as a simple response bias, a central tendency effect (Hollingworth, 1910; Tong & Dubé, 2022), or a generic high-level decision/memory phenomenon: it depends strongly on location (including retinotopic location); it is highly specific to the particular stimulus and the similarity between sequential stimuli; and, it spreads across across several trials with independent stimuli. Hence, if serial dependence is a purely high level effect in decision or memories, it must take the spatial, temporal, and stimulus selectivity interactions into account, but those properties are more commonly associated with earlier processing. On the other hand, serial dependence cannot be considered as a purely low-level phenomenon either: as shown in the initial foundational study (Fischer & Whitney, 2014), attention plays a crucial role (Figure 9), as do many other high-level factors such as confidence (Samaha et al., 2019), awareness (Fornaciai & Park, 2019a; Kim et al., 2020), memory (Bliss et al., 2017; Fritsche et al., 2017; Mei et al., 2019), among others. As previously mentioned, it may well that serial dependence is not a unitary, singular, or modular construct, but there may be different forms of serial dependence implemented for different stimuli at various levels of processing (Figure 1), as well as different manifestations on action, perception, decision and memory (Kiyonaga et al., 2017; Liberman et al., 2014; Manassi et al., 2018a).

Sequential effects that are not serial dependence

Not every history effect in perception and memory is serial dependence. There are countless priming effects (Bargh, 2014; Budescu, 1985; Cross, 1973; DeCarlo & Cross, 1990; Garner, 1953; Ward & Lockhead, 1971) that exist but do not display the same tuning properties. For example, some forms of priming only speed responses or extend everywhere in space, and are therefore not tuned in the same fundamental ways as serial dependence. Based on our meta-analysis, some phenomena and psychological effects that are reminiscent of or vaguely similar to serial dependence can be easily distinguished because they do not conform to the concrete operational definition of serial dependence. That said, it is also possible that many previously studied phenomena, including some forms of priming, could actually be caused by serial dependence. Priming is thorny and does not have a set of universally agreed diagnostic criteria, and the jury is still out on which types of priming may actually be serial dependence.

In addition to history effects that are not serial dependence, there are also many types of stochastic biases in vision that are not serial dependence, such as oblique effects in the orientation perception (Appelle, 1972; Furmanski & Engel, 2000; Heeley et al., 1997), localization biases (Kosovicheva & Whitney, 2017), idiosyncratic stimulus-related biases (Wang et al., 2020, 2022), and anchoring effects in numerosity (Sawyer & Wesensten, 1994) and face perception (Goller, Leder, Cursiter, & Jenkins, 2018). These biases can be at the group level or at the individual observer level, but they are not serial dependence and should not be conflated with it because they do not display the diagnostic properties revealed by the meta-analyses here.

Other biases, such as predictability and edge effects in prothetic stimulus distributions, regression to the mean, central tendencies, anchoring effects, and stereotyped responses can produce artifacts that, on cursory inspection, seem to be serial dependence (Glasauer & Shi, 2020; Maus, Chaney, Liberman, & Whitney, 2013), but they are not (Berliner & Durlach, 1973; Hollingworth, 1910; Williams, Phillips, & Sekuler, 1986). A number of these sorts of biases and artifacts have been thoroughly discussed in the serial dependence literature (Collins, 2022b; Fritsche et al., 2017; Glasauer & Shi, 2020; Liberman et al., 2014; Maus et al., 2013; Pascucci et al., 2019), and most studies control for them in a variety of ways including experimentally, analytically, and statistically (Cicchini et al., 2017; Collins, 2022b; Fritsche et al., 2017; Manassi et al., 2018a; Pascucci et al., 2019; Xia et al., 2016). Serial dependence should not be confused with these artifacts.

Adjudicating between debates

There are many debates in the serial dependence literature. One of the more extensive ones is whether serial dependence happens in sensory processing, perceptual awareness, decisions, memory, action, or at many of these stages (Bliss et al., 2017; Cicchini et al., 2017; Cicchini et al., 2021; Fornaciai & Park, 2018a; Fritsche et al., 2017; Kim et al., 2020; Kiyonaga et al., 2017; Manassi & Whitney, 2022; Murai & Whitney, 2021; Pascucci et al., 2019; Pascucci et al., 2023). There is even a question about whether these “stages” are even valid distinctions, given the prevalence of feedback and reentrant processing in vision and the involvement of attention in serial dependence (e.g., Figure 9). Additional debates continue about where serial dependence happens in the brain (Barbosa et al., 2020; Braun, Urai, & Donner, 2018; Ceylan et al., 2021; de Azevedo Neto & Bartels, 2021; Fornaciai, Togoli, & Bueti, 2023; John-Saaltink et al., 2016; J. Luo & Collins, 2023; Sheehan & Serences, 2022; van Bergen & Jehee, 2019), how many different forms of serial dependence there are, and whether it is just another word for some other history effect like priming (Galluzzi et al., 2022) or central tendency (Tong & Dubé, 2022). Whereas our meta-analysis does not take a position in this respect, we believe all of these debates are clarified and better served with the diagnostic criteria firmly established by the meta-analyses here. Serial dependencies are an operationally defined family of phenomena that reflect an underlying set of mechanisms, and they can be distinguished from other effects in virtue of their tuning properties.

Conclusions and future directions

The meta-analyses here conclusively documented the presence of serial dependence in many domains, from perceived orientation (Figure 2) to face recognition (Figure 3) and numerosity (Figure 4), and they provide a window on the tuning properties of serial dependence (Figures 6–9). The meta-analyses also reveal a number

of yawning gaps in the literature, including fundamental questions about possible variation in tuning properties for different features and objects, among many other questions. In deference to the significant number and depth of the questions that remain about serial dependence, we conclude with a section on future directions (Box 1). In light of these, the meta-analyses reported here are guideposts, revealing diagnostic criteria that can be used to help focus important future questions on the mechanisms and pragmatic role that serial dependence plays in perception, decisions, cognition, and action.

Keywords: serial effects, sequential effects, serial dependence, sequential dependencies, stability, stabilization, perceptual stability, priming, hysteresis, anchoring

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Footnote

[1] The single unique exception to this criterion is panel A in Figure 10, which includes one conference poster for illustration (Manassi et al. 2018b), because the sample size in that study is the largest known using a single design in the orientation domain. That study was not included in any other meta-analysis reported here.

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