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Uncertainty In Serial Dependence

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Abstract

Serial dependence refers to an assimilation to prior stimuli in current perceptual decisions. This assimilative bias is theorised to occur because the recent past can act as a useful guide to the current state of the world, and so may be used to smooth over meaningless noise in perception. For this process to be truly optimal it should take into account the level of uncertainty associated with stimuli in a way that roughly follows a process of Bayesian inference.

In this thesis experiments are carried out to determine if serial dependence is sensitive to uncertainty in a way that might allow for a Bayesian mechanism to dictate the strength of this bias. A series of experiments using orientation stimuli demonstrate the sensitivity of serial dependence to confidence in the prior stimulus judgement, and objective uncertainty in the current stimulus. This is suggested to be because objective uncertainty represents the best available measure of current stimulus uncertainty at the time of a decision. In prior stimuli, confidence represents a better measure of uncertainty as it may be derived from further post-decisional evidence processing. The combined impact of prior confidence and current uncertainty might allow serial dependence to be regulated in a way that conforms to the predictions of a Bayesian model.

Experiments were also carried out to determine whether this bias is the result of a low-level perceptual effect or an attractive effect of prior decisions. These experiments suggest that serial dependence is best quantified as an attraction to the prior response. However, it remains unclear if this attraction to responses represents a bias towards the prior decision or the prior percept. The observed sensitivity of serial dependence to confidence and feedback might suggest a higher-level basis to this effect.

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Author's Declarations

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: ____ DATE: 21/04/2023

Publications

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This publication is included here as Chapter 2. I was responsible for the design, rationale and construction of the experiments, with the support of my supervisor Chris Benton. I undertook all data collection and analysis. I produced the initial draft of the paper which Chris then provided feedback on. After submission I further edited this paper based on feedback from peer reviewers. This publication has been edited to fit with the rest of the thesis.

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Chapter 1. Introduction

1.1. What Is Serial Dependence?

Visual perception is an inherently noisy process: our surroundings are highly dynamic, head and eye movements create further variation in visual input, the receptors which we use to perceive the world respond to an unpredictable stream of photons, and neurons themselves are subjects to fluctuations in activity. Noise is therefore present at all stages of vison, from movements in the objects of visual perception through to neural noise in the organs which we use to perceive them (DeValois et al., 1991). Nevertheless, we generally perceive a stable visual world, free of inconsistent changes.

Regularities in the visual environment can be exploited to smooth over noise in relatively stable stimuli (Dong & Atick, 1995; Girshick et al., 2011). If a car passes between you and a friend on the other side of the road it is safe to assume that the same person reappears once the car has moved; the visual features of this person are likely to remain consistent. Using regularity to effectively ignore intermittent noise may be a computationally efficient way for the brain to generate stable visual perception (Burr & Cicchini, 2014; J. Fischer & Whitney, 2014).

Serial dependence is one way that the brain might exploit environmental regularity (J. Fischer & Whitney, 2014). When presented with a sequence of stimuli, the perception of the current stimulus can be affected by similar prior stimuli. Although the umbrella term “serial dependence” could accurately describe repulsive or attractive effects resulting from sequential stimulus presentation, the term is more recently used to refer to positive perceptual attraction towards recent, distinct perception. For example, on presenting participants with Gabor patches of different orientation, Fischer and Whitney (2014) found that when orientation differences were within a certain range, the reported orientation of a patch was erroneously drawn towards the prior patch, away from the true value. Importantly this effect is unlikely to be caused by a simple confusion of the current stimulus with the previous. Simulations by Fornaciai and Park (2020b) demonstrated that such "swap errors" were not able to account for serial dependence effects. Instead, observer response errors indicate that a perceptual blending of current and current and prior stimuli may be occurring.

Despite producing errors, serial dependence may be useful as the recent past is often an accurate predictor of the present and, due to noise, minor changes in visual input may not signal genuine change in the observed stimulus (Treisman & Williams, 1984). Furthermore, If the differences between sequentially presented stimuli are too large then serial dependence does not occur and perceptual repulsion away from the prior stimulus may even take place (J. Fischer & Whitney, 2014). This suggests that serial dependence may in fact be a strategy used by the visual system to correct for minor instabilities in visual information (Burr & Cicchini, 2014; Cicchini & Kristjánsson, 2015; Fritsche et al., 2017). Put simply, serial dependence assumes that the present resembles the past in order to avoid “overfitting” the data and treating every minor fluctuation in visual input as a meaningful change (Alais et al., 2018).

Many of the features of serial dependence lend themselves towards the idea of a practical mechanism for perceptual stabilisation. Demonstrating the potential utility of serial dependence, Liberman et al. (2016) conducted a study in which a moving stimulus was temporarily obscured by an occluder. In this case a Gabor patch moved horizontally across a screen, until it was obscured by a black bar occupying the middle of the screen. Another Gabor then emerged horizontally from the other side of the black bar following the same trajectory. This sequence of events emulated a natural scenario where serial dependence might take place; an observer’s view of an object is temporarily interrupted. Serial dependence could then aid the observer in maintaining their perception of object properties despite movement behind a temporary occluder. Participants completed an adjustment task to reproduce the orientation of the second Gabor, which demonstrated that the perceived orientation of the second Gabor was attracted towards the unrelated random orientation of the first Gabor. Consistent with earlier work by Guo et al. (2004), which showed an assimilative effect when orientation stimuli followed a predictable spatio-temporal path, Liberman et al. found that Serial dependence was stronger in Gabor patches which appeared to move with more predictable, unbroken trajectories. This study demonstrates that serial dependence relies on the assumption that stimuli in the environment behave in a predictable way.

This may be consistent with the view that this effect is restricted to instances of items that can be reasonably considered to be the same object. In a series of experiments, Collins (2021) demonstrated reduced serial dependence for emotional expression with different facial identity, as well as reduced shape serial dependence with different orientations. This suggests that a combination of features conducive to the interpretation of one persistent object might promote serial dependence. However, Pascucci et al. (2023) note that this may be task dependent, with object identity influencing serial dependence when beneficial given the demands of a task.

The range of this effect may be limited in a pragmatic way. Fischer and Whitney (2014) describe serial dependence in orientation judgements occurring over a limited spatial region referred to as the “continuity field”, where current perception is attracted towards the recent past (Kiyonaga et al., 2017). Limiting the range of serial dependence may prevent it from “blending” distinct perceptual items. There is also a temporal dimension to the continuity field as attraction only occurs between percepts within a small window of time (Bliss et al., 2017; J. Fischer & Whitney, 2014). Ortega et al. (2023) provide evidence that the time course of serial dependence follows that of naturally occurring autocorrelations. This bolsters the idea that serial dependence is intended to smooth over aberrations in sensory information in a way that conforms to realistic expectations about the environment.

Initial work by Fischer and Whitney suggested that the continuity field operates on spatial coordinates (spatiotopic) rather than being mapped to retinal coordinates (retinotopic) (J. Fischer & Whitney, 2014). Spatiotopic mapping is believed to have strong links to attention (Melcher & Morrone, 2015). This is consistent with the necessity of attention for serial dependence (J. Fischer & Whitney, 2014). However recent experiments comparing successive spatiotopic and retinotopic image stimulus presentations suggest a degree of retinotopy in the continuity field, albeit covering a broad area of visual angle (Collins, 2019).

Potential differences in the tuning of the continuity field, as well as differences in the pattern of responses in different stimulus types, have been taken as a sign of domain specificity in serial dependence rather than a cross-perceptual mechanism (Togoli et al., 2021). This has been taken to imply a low-level perceptual basis to this effect (Fornaciai & Park, 2020b) Importantly, stability of stimuli may vary for different stimulus classes and a catch-all approach might not be appropriate. Certain stimuli might be expected to undergo change over the short timescales where serial dependence might apply, meaning that assimilative biases are not beneficial. In this case a domain-general bias might be detrimental compared to multiple serial effects tuned to different stimulus types (see Flexibility in Serial Dependence below).

Although initially described in orientation stimuli, serial dependence is not limited to orientation and may apply to a large array of perceptual features. Kondo et al. (2013) found that sequential effects can apply across very subjective aspects of perception, such as facial attractiveness, as well as features with a more objective basis, such as face roundness. These effects are also not limited to visual stimuli as similar serial influences have also been demonstrated in the auditory (Arzounian et al., 2017; Holland & Lockhead, 1968; Motala et al., 2020) and even olfactory domains (Van der Burg et al., 2022). Appendix Table A1 shows a range of stimulus types which have been shown to exhibit serial dependence. Apparent errors in perception produced by this effect may therefore be widespread.

Across different stimulus types, the pattern of errors produced by serial dependence is fairly consistent. Fischer and Whitney (2014) found that errors made due to serial dependence in orientation judgements could be roughly modelled by a derivative of Gaussian function, as shown in Figure 1.1. this function describes a pattern of errors which are consistent with the previous stimulus; when the previous stimulus was clockwise of the current stimulus, participants tended to make clockwise errors, and vice versa. Other analytical approaches have also been applied to incorporate additional repulsive biases which may occur at large stimulus differences (Bliss et al., 2017) or to avoid the assumptions of model-based approaches while still capturing this biasing of errors (Samaha et al., 2019).

In their initial work characterizing serial dependence, Fischer and Whitney (2014) proposed gain and shift models of orientation tuning to explain the observed pattern of errors (Figure 1.2). These models describe serial dependence as an effect resulting from interactions between low level perceptual units, such as orientation-tuned neural populations in visual cortex, which preferentially respond to specific stimulus features. The combined output of a population of these selective channels determines the perceptual response to the stimulus. In the case of orientation, if channels selective for the range around 90 were responding strongly while other channels remained relatively unresponsive then the population response would likely be biased towards this value. This would lead the observer to perceive an orientation of 90 degrees.

The gain and shift models of Fischer and Whitney describe how previous exposure to stimuli can change the response profile of perceptual channels in a way that leads to serial dependence. The gain model relies on enhanced responsivity in previously activated channels, whereas the shift model relies on a transient change in channel tuning (see Figure 1.2). Both mechanisms skew the population response, and hence the perception of subsequent stimuli, towards the previous viewed stimulus. Both models used by Fischer and Whitney ultimately produce the same result: current perception is attracted towards previous as long as both are within a narrow stimulus range.

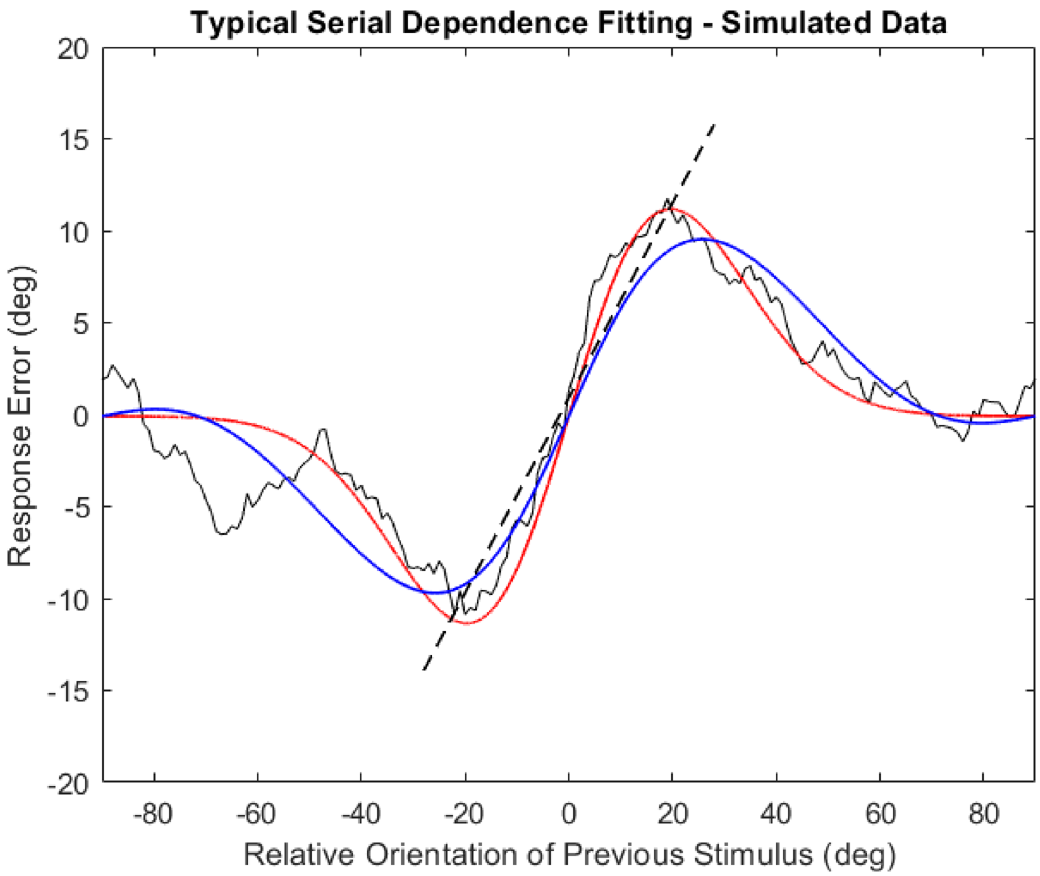

Figure 1.1. Participant response error plotted against the orientation of stimuli relative to the previous stimulus. Fischer and Whitney found that serial dependence followed a flipped derivative of gaussian curve (red line). When the difference between current and previous stimuli was negative so were the errors committed by participants and vice versa. Alternative models such as the Clifford curve (blue line Bliss et al., 2017; Clifford et al., 2000) or simple linear fits (dashed line Fornaciai & Park, 2020b; Kim et al., 2019) have also been applied to quantify this effect. Simple model free analyses which count the occurrence of errors in the direction of the previous stimulus have also been utilised (Samaha et al., 2019). Different models may be appropriate for different stimulus categories as stimulus tuning may vary (Fornaciai & Park, 2020b). Note that the magnitude of this effect may also vary with different experimental paradigms and within participants (Bliss et al., 2017; Pascucci et al., 2023).

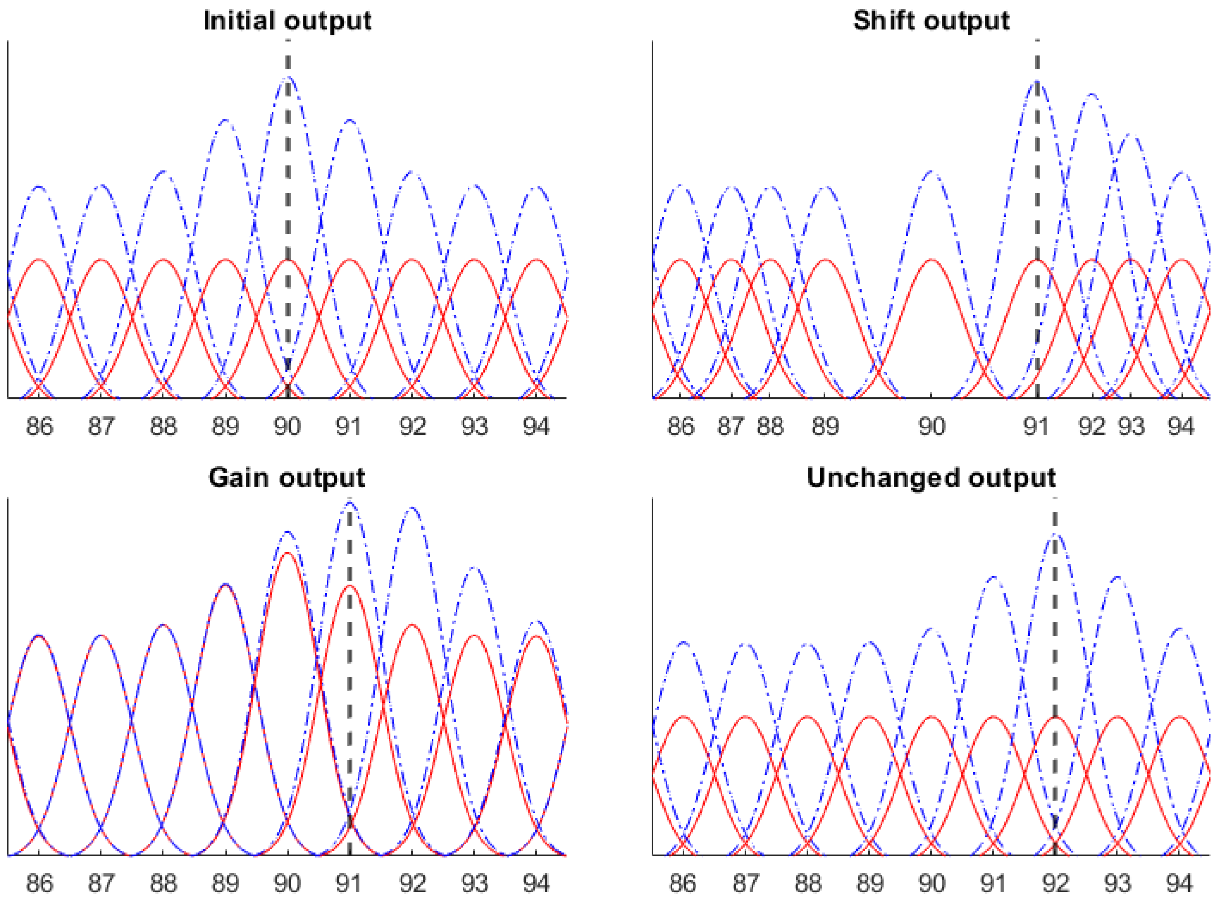

Figure 1.2. The pattern of orientation responsive channel responses before and after gain and shift patterns are applied is shown. Top left shows the initial sensitivity of orientation selective channels (red curves) and their response to a 90° stimulus (blue curves). Top right shows how stimulation by a 90° stimulus might alter the initial pattern of channel sensitivity if a shift in channel responsiveness occurs (red curves). The expected output of these channels in response to a 92° stimulus is shown (blue curves). Bottom right shows how a change in gain in response to a 90° stimulus might alter the initial responsiveness of channels (red curves) and their output in response to a 92° stimulus. Bottom right figure shows the initial responsiveness (red curves) and output upon exposure to a 92° stimulus (blue curves) if neither gain nor shift patterns were applied in response to stimulation by and initial 90° stimulus. The peak response of neural populations is represented by a dashed black line in all images.

1.1.1. Could other sequential perceptual effects account for serial dependence?

A number of other effects on perceptual report can also arise from sequential stimulus presentation over similar timescales to serial dependence. There is significant overlap between typical serial dependence experimental procedures and experiments aimed at investigating other areas of cognition. Studies investigating phenomena such as confirmation bias, adaptation, and priming may use very similar procedures. Similarities between these studies likely reflect the fact that they are investigating aspects of the same complex process of perceptual inference over short timescales (Bae & Luck, 2017; J. Fischer & Whitney, 2014; Luu & Stocker, 2018; Talluri et al., 2021). This raises the obvious question of whether one of these other effects might provide an explanation for serial dependence. Some of these effects may operate in opposition to serial dependence, others may arise from similar mechanisms, or could even just be serial dependence by another name.

1.1.1.1. Anchoring

Assimilative effects from prior stimuli have been referred to as anchoring effects (Huang et al., 2018). Anchoring is an effect whereby previous experience influences current responses. Perception of initial stimuli creates a bias which causes subsequent stimuli to be judged relative to the first. Responses may be assimilative or repulsive based on similarity to the initial stimulus (Sherif et al., 1958). Anchoring generally involves using the first stimulus in a sequence as a reference against which to judge all subsequent stimuli (Tversky & Kahneman, 1974). Tversky and Kahneman (1974) suggest that adjustments of the internal reference can be made, but that they are influenced by the initial stimulus. In contrast, serial dependence suggests a more active updating procedure, where current choice is influenced by the previous stimulus but much earlier elements in the sequence are less influential. Multiple studies suggest the influence of a previous stimulus on the current trial dissipates after a small number of intervening trials (J. Fischer & Whitney, 2014; Manassi et al., 2018; Pegors et al., 2015).

1.1.1.2. Adaptation

Discussion of previous stimuli influencing present perception invites comparisons to other well-known perceptual mechanisms. Adaptation is one such perceptual effect whereby exposure to a stimulus pushes perception of following stimuli in the opposite perceptual direction. Perhaps the most straightforward example of adaptation is the waterfall illusion (Addams, 1834). When viewing a moving stimulus such as a waterfall for a long period of time, the visual system can adapt to the consistent downward motion perceived. Adaptation to downward motion then causes stationary objects to appear to move upwards.

Adaptation therefore seems to act in opposition to attractive serial dependence. Whereas serial dependence causes subsequent stimuli to be perceived as more similar to previous stimuli than they actually are, adaptation causes a bias in the opposite perceptual direction. Clifford et al. (2000) highlight the fact that adaptation may enhance sensitivity to change. Serial dependence and adaptation may act to counterbalance each other, allowing maintenance of a stable percept while allowing for the possibility that the environment may change with time (Alais et al., 2017; J. Fischer & Whitney, 2014; Fritsche et al., 2017). Despite this potentially antagonistic relationship, it must be noted that serial dependence does not suppress sensitivity to changes of sufficient magnitude (J. Fischer & Whitney, 2014). This suggests that there are reasonable limits to each of these serial effects that might allow them to exist simultaneously. Moon and Kwon (2022) describe how this might arise from differences in the tuning of serial dependence and adaptation, with repulsive effects arising from a change in stimuli beyond the tuning range of serial dependence. The visual system might even consider adaptation when constructing perception. Sheehan et al. (2022) built a model of serial dependence based on their observation of neural indications of adaptation (a repulsive effect) alongside seemingly contradictory behavioural indicators of serial dependence (an assimilative effect). The authors concluded that serial dependence arises from a process which takes into account low level neural adaptation and compensates for it when producing visual perception.

1.1.1.3. Change Blindness/Inattentional Blindness

Change blindness (Rensink et al., 1997) and inattentional blindness (Neisser, 1979) occur when observers fail to notice obvious changes in stimuli (Simons & Chabris, 1999). Despite superficial similarities in description, serial dependence is likely distinct from these effects. Although inattentional blindness also involves an apparent misperception of environmental change, serial dependence explicitly depends upon attention to the changing stimulus (J. Fischer & Whitney, 2014). Perception is often interrupted in serial dependence, but attention to the stimulus locus, or expected locus, (Liberman et al., 2016) is maintained. Inattentional blindness occurs when a stimulus is directly viewed but attention is otherwise occupied (Most, 2010).

Change blindness also differs from serial dependence. Change blindness has been reported to obscure fairly major changes in a scene (Andermane et al., 2019), whereas serial dependence masks very small stimulus changes with subtle assimilative effects on perception. Large changes are actually more likely to cause a repulsive effect in the case of serial dependence (J. Fischer & Whitney, 2014).

1.1.1.4. Central Tendency

Central tendency refers to a phenomenon whereby responses can be drawn towards the mean of a sequence of stimuli (Hollingworth, 1910). As a rough example, if an observer were to see a sequence of orientation stimuli: 0°, 10°, 80°, 90°. The observer's response to a subsequent stimulus may be attracted towards the mean of previous stimuli, 45°.

Tong and Dube (2021) suggest that serial dependence and central tendency might be attributable to the same underlying process. The authors suggest that responses are made based on a weighted moving average of current and recent stimuli. This can appear to produce a central tendency effect as this moving average is likely to resemble the overall mean of stimuli. Giving recent stimuli more weight in the moving average can produce a serial dependence effect. However, Kristensen et al. (2021) identified separate influences of central tendency and serial dependence in size perception. By subtracting the predicted influence of central tendency on responses, the authors were able to identify a serial dependence effect present in their data. Other work has also identified central tendency and serial dependence as separate factors each with distinct influences on perception (Motala et al., 2020). Studies have specifically investigated individual differences in the scale of these two effects (Glasauer, 2019), and both effects may exhibit independent differences in strength in non-neurotypical individuals with different conditions (Lieder et al., 2019).

To rule out any causal relationship between the two effects, studies of serial dependence have used manipulations of prior stimulus order, something which could alter serial dependence from prior trials but which should not affect central tendency, which is a product of the full set of stimuli displayed (Manassi & Whitney, 2022). Equivalent analysis techniques may also be able to rule out the influence of central tendency; randomly permuting data typically removes any observed serial effects (Alais et al., 2021; Ortega et al., 2023). By manipulating stimulus order in this way these experiments have shown that observed serial dependence effects cannot be attributed to central tendency.

1.1.1.5. Priming

Perceptual priming can occur when the features of initial stimuli facilitate responses to subsequent stimuli via an attentional mechanism (Kristjánsson & Campana, 2010). Multiple authors have compared serial dependence and priming while noting that the effects of the latter typically manifest in reaction time rather than perception (J. Fischer & Whitney, 2014; Kristjánsson & Ásgeirsson, 2019). Reaction times may be quicker for congruent stimuli in priming experiments, whereas serial dependence produces an effect in the interpretation of stimuli. A key distinction made by Fischer and Whitney (2014) is that priming can produce improvements in reaction time or discriminability, whereas serial dependence actually represents a reduction in discriminability as two stimuli which are very similar, but distinct, are conflated in serial dependence experiments.

However, there may be reason to suspect that the differences between these sequential effects are not so stark. There are some data to suggest that serial dependence may also be accompanied by improvements in reaction time (Cicchini & Burr, 2018). Similarly, Kristjánsson and Ásgeirsson (2019) review research suggesting possible perceptual effects of priming. These similarities blur the distinction between serial dependence and priming, raising the possibility of a relationship between the two.

Priming and serial dependence might also be subject to similar constraints. Multiple studies suggest that a similarity in stimulus orientation necessary for priming to occur may cover a similar range to serial dependence. Tanaka and Sagi (1998) mention that orthogonally oriented Gabor patches do not prime detection of subsequent Gabor patterns, in contrast to similarly oriented Gabors which do aid detection. Gauthier and Tarr (1997) show that non-Gabor stimuli exert greater priming effects when orientation is similar to the target stimulus. Tanaka and Sagi (2000) suggest that stimuli with similar orientations can prime subsequent stimuli, however if the orientation difference is too large, suppressive effects can instead occur. This pattern of stimulus influence resembles the relationship between stimuli in serial dependence as similarly oriented stimuli can cause serial dependence, however this breaks down if the orientation difference becomes too large (J. Fischer & Whitney, 2014). Similar behaviour suggests that either the same mechanism is responsible for these effects or that both operate according to constraints based on how useful recent visual experience is likely to be.

One way in which priming does seem to differ from serial dependence is that prior stimuli can produce a priming effect without having to be consciously perceived. Stimuli which are masked so that they never reach conscious awareness still induce priming (Bar & Biederman, 1998). In contrast, serial dependence may rely on prior perception (see Decision Effects 1.1.2.2 below) and be eliminated by masking (Fornaciai & Park, 2019a). Potentially related to this apparent dependence on prior perception, Feigin et al. (2021) suggest a key distinction between serial dependence and priming: serial dependence, according to some interpretations, requires an intentional choice (see Decision Effects below), whereas priming can be produced by stimuli alone, whether consciously perceived or not.

Priming may also differ from serial dependence in how many subsequent trials can be affected by the initial stimulus. Although differences have been found in how far back serial dependence effects occur, the number of previous trials (2-4 trials back) which can affect current perception is generally low (J. Fischer & Whitney, 2014; Manassi et al., 2018; Pegors et al., 2015). Maljkovic and Nakayama (1994) showed that priming can occur from stimuli presented at least five trials back, despite distractors being presented between prime and target. Priming may therefore operate over a longer temporal integration window than serial dependence.

Additionally, Fornaciai and Park (2019b) suggest that, although priming can cross sensory modalities in numerosity perception (Kouider & Dehaene, 2009), there is segregation between visual and auditory serial dependence in this domain. Auditory and visual representations of numerosity did not produce serial dependence across modalities suggesting a distinction from the mechanisms responsible for priming effects in numerosity. Similar research from Lau and Maus (2019) also suggests segregation between serial dependence in different modalities.

Finally, Galluzzi et al. (2022) suggest that priming and serial dependence are mediated by distinct mechanisms. Manipulating stimulus features such as colour was shown to enhance priming while leaving the magnitude of serial dependence unaffected.

Although priming is in some ways similar to serial dependence, the differences listed above suggest that these two effects are distinct. Similarities between the two effects may arise from similar constraints on perception over short timescales. The maintenance of two different systems with similar goals may be permitted due to the distinctions between them. To rely purely on serial dependence or priming rather than both might cause deficits in areas such as response times or cross modal recognition.

1.1.1.6. Confirmation Bias

The term confirmation bias has been used to refer to a range of different behaviours whereby evidence is sought, interpreted, or recalled in way that is consistent with expectations or previous beliefs (Nickerson, 1998). Recent studies have referred to a form of confirmation bias involving the influence of categorical choices upon subsequent perception (Talluri et al., 2018, 2021) In this case confirmation bias produces similar outcomes to serial dependence following categorical judgements. After making an explicit categorical choice, observers may be more likely to make a similar, choice on a following task which may not be categorical.

Talluri et al. (2018) found that confirmation bias may arise through selective application of attention to stimulus features that are consistent with features of stimuli in previous categorical choices. So, if you were to decide that a small furry animal is a cat, the next time you see an animal you might pay attention to its fur, tail and other cat-like features, while ignoring any barking. The study of Talluri et al. used stimuli and procedures very similar to those used in typical serial dependence tasks (J. Fischer & Whitney, 2014; Fritsche et al., 2017). A categorical choice was made (clockwise or counterclockwise) on the direction of motion stimuli. This was followed up with an adjustment task where participants had to match the direction of motion that they had just seen. In serial dependence tasks participants often complete an adjustment task before making a categorical choice (J. Fischer & Whitney, 2014; Fritsche et al., 2017). The similarity of this experiment to serial dependence studies, as well as similar assimilative response outcomes in both cases, suggests that these serial effects could be the result of the same process.

The key difference in the literature between this form of confirmation bias and serial dependence is that initial tasks in serial dependence studies involve reproducing stimulus features, whereas confirmation bias experiments involve assigning a stimulus to a broad category. There may be good reason to make a distinction between stimulus reproduction and categorisation; assigning items to categories produces effects on discrimination based on category boundaries (Goldstone & Hendrickson, 2010; Jones et al., 2006). Differences amongst group members may be minimised, while across category boundaries differences between items may be exaggerated. Although some effects observed in categorisation tasks may be relevant to serial dependence, categorisation implies differences in perceptual processing. Similarity between successive stimuli could prompt an observer to select the same category for them, whereas dissimilarity may cause an observer to believe stimuli come from different categories (Hsu & Wu, 2020).

Nevertheless, there remain similarities in the effects of confirmation bias and serial dependence. In a face categorisation experiment Hsu and Wu (2020) found a pattern of attractive or repulsive sequential effects dependent on the scale of prior stimulus similarity, resembling the pattern observed in serial dependence (J. Fischer & Whitney, 2014). This implies that if categorical sequential effects do differ from serial dependence, then they at least follow similar rules. Additionally, Zotov et al. (2011) demonstrated cross-task sequential effects using categorical choice and production tasks, this suggests that results of perceptual confirmation bias studies and serial dependence experiments may be applicable to each other. In addition, some perceptual decisions made in serial dependence studies are arguably categorical, such as facial identity or expression choices. If serial dependence is based on a sequential effect in choice (see Decision Effects below) then there may be common theoretical ground for these two effects, which are perhaps separated only in terminology.

1.1.1.7. Hysteresis

Serial dependence resembles perceptual hysteresis, a perceptual effect which occurs when a previously perceived stimulus persists despite a reduction in visibility or stimulus intensity (Kleinschmidt et al., 2002). In a typical hysteresis experiment a property of the stimulus, such as contrast, would be reduced until the stimulus can no longer be perceived or the previous interpretation of the stimulus switches (in the case of bistable stimuli). The change is then steadily reversed until the observer reports being able to perceive the initial stimulus again. Observers typically require a higher level of contrast to regain their initial perception of the stimulus than the contrast level at which they reported being unable to perceive it previously. The perception of the stimulus is “stretched” past the point at which observers later report it as being discriminable. Although this blending of past and present stimuli is similar, the key difference between hysteresis and serial dependence is that stimuli are typically suprathreshold and unambiguous in examples of serial dependence, as opposed to the ambiguous stimuli which are used to elicit hysteresis (Collins, 2021). Nevertheless, both effects represent a lingering effect of prior stimuli on current perception (J. Fischer & Whitney, 2014). Some authors use the terms hysteresis and serial dependence interchangeably (Pascucci et al., 2023; Trapp et al., 2021; Van Geert et al., 2022) leaving little distinction between these two effects.

1.1.1.8. Proactive Interference

Serial dependence has been described as a form of "proactive interference" (Bliss et al., 2017; Kiyonaga et al., 2017). This term refers to the way in which multiple items held in working memory may interfere with each other (Jonides & Nee, 2006). This could roughly describe serial dependence; the memory of the previous trial stimulus interferes with reproduction of the stimulus observed on the current trial. However, Fischer et al. (2020) make several distinctions between serial dependence and proactive interference. Firstly, proactive interference seems to arise from assigning an item on the previous trial to the current trial. This is subtly different from serial dependence where a blending between items appears to occur rather than a swapping out of memory items. In addition, Fischer et al. describe proactive interference as mainly arising from non-target items whereas serial dependence is mainly described in relation to the previous target item. Despite these distinctions, Fischer et al. report a responsiveness of serial dependence to context, something which is known to apply to proactive interference. Kiyonaga et al. (2017) suggest that serial dependence and proactive interference could be produced by the same mechanism, with the maintenance of irrelevant items occurring in proactive interference representing a maladaptive form of an otherwise useful process.

1.1.1.9. Overview

Several perceptual effects bear a resemblance to serial dependence. Adaptation appears to act in opposition to positive serial dependence. This antagonistic relationship could actually be co-dependent, with adaptation acting to enhance sensitivity to change while serial dependence serves to maintain perceptual continuity, each balancing the other out. Priming, confirmation bias and hysteresis all seem to produce similar outcomes in facilitating one perceptual response over another. It is possible to distinguish between these effects based on behavioural outcomes listed above. It remains unclear whether these effects appear related due to a common mechanism or because all are operating within similar perceptual constraints. It may be the case that several attractive mechanisms subserve the same general rule: the world is relatively static and can act as a useful guide to the past (Whitney et al., 2022). If this is the case, then strong repulsive effects such as adaptation may act to counter this assimilative tendency and prevent compounding of errors.

1.1.2. Non-perceptual explanations for positive serial dependence

Although other sequential effects, such as adaptation, appear to be low-level perceptual effects, the nature of serial dependence remains a topic of debate. Initial work by Fischer and Whitney described serial dependence as a perceptual effect. Later work has characterised this effect slightly differently, invoking post-perceptual explanations such as attractive effects between decisions, or blending of working memory representations rather than percepts. Experimental evidence has been argued to show that serial dependence arises from a direct perceptual process (Cicchini et al., 2017; J. Fischer & Whitney, 2014) or from post-perceptual processing (Alais et al., 2017; Fritsche et al., 2017; Pascucci et al., 2019).

1.1.2.1. Serial Motor Effects

To clarify the sort of non-perceptual explanation for positive serial dependence that authors such as Fritsche et al. (2017) argue for, it is useful to first describe non-perceptual effects that are usually ruled out in serial dependence studies which apply appropriate methodology. Serial dependence experiments have typically sought to distinguish serial perceptual distortions from non-perceptual effects which can arise from sequential stimulus presentation. For example, it is possible that repetition of a perceptual report could result from a tendency to act out the same motor responses.

Serial motor effects have been demonstrated in two alternative forced choice (2AFC) perceptual decisions by Pape et al. (2017). Similar conclusions were reached by Huang et al. (2018) who suggest that assimilative serial effects may be reduced (but not eliminated) when responses consisted of oral reports rather than button presses, hinting at a motor contribution to serial effects. Studies of serial dependence have tried to rule out motor responses biases by alternating required responses, by changing the position of options presented, or including no-response trials. In no-response trials stimuli are displayed but no motor response is required on a random selection of trials, typically a fixation point is shown rather than a response stimulus (J. Fischer & Whitney, 2014; Liberman et al., 2014; Xia et al., 2016).

Alternation of responses may be preferable to no response trials, as the former procedure provides a measure of participant perception on the previous trial. This is necessary to establish that serial dependence is occurring between serial perceptions of stimuli rather than between stimuli (which may be perceived differently than their objective appearance). Cicchini and Burr (2017) asked participants to reproduce mirrored orientations; rather than replicating the orientation they had just seen, participants had to produce the orientation flipped around the vertical axis. Alternating mirrored/non-mirrored orientation reproductions still produced serial dependence for similar stimuli despite differences in motor response. Similarly, Feigin et al. (2021) alternated judgements between colour and location of an onscreen disk while keeping response buttons the same. The aim of this procedure was inducing a motor bias in button response across judgement types to see if this could account for serial dependence normally observed within repetitive judgements. The authors found a small positive bias, however this was non-significant. In contrast, performing the same judgement via different motor actions did produce a significant serial effect.

These basic procedural considerations can be used to dismiss obvious non-perceptual serial biases, such as motor effects or a preference for a specific response. With these options ruled out, we can consider other ideas about the origins of serial dependence.

A major argument surrounding serial dependence is whether this process occurs at a perceptual or post-perceptual stage of processing. To broadly summarise the key question in this debate: does serial dependence bring about a genuine perceptual change at the time of observation or do serial effects instead change later aspects of stimulus processing, such as the memory of the stimulus or decisions made in response to the stimulus?

While the typical pattern of errors caused by serial dependence might suggest a change in perception, the fact that this effect is thought to occur across such diverse stimulus types as orientation (J. Fischer & Whitney, 2014), facial attractiveness (Xia et al., 2016), food appraisal (Van der Burg et al., 2021) and monetary value (Morimoto & Makioka, 2022) could suggest an amodal process generally affecting perceptual decisions rather than low-level perceptual effects (Fornaciai & Park, 2020b). Some experimental data does support this view; Ceylan et al. (2021) demonstrated serial dependence occurring across different representations of orientation (Gabor and dot pattern stimuli). Similarly, Fornaciai and Park (2022) demonstrate attractive effects occurring across symbolic and non-symbolic representations of numerosity. These results may be taken as evidence that serial dependence operates at a higher, more abstract, level of processing beyond basic stimulus features. This has led to theories of serial dependence based on higher level/top-down factors (Bosch et al., 2020; Fritsche et al., 2017; Pascucci et al., 2019). These top-down effects may be hard to distinguish from low-level perceptual effects when perception and response are tightly coupled (Fritsche et al., 2017; Morimoto & Makioka, 2022).

1.1.2.2. Decision Effects

Although serial dependence initially appears to be a sensory phenomenon, it could just be a change in the way in which perceptual decisions are made. Well documented serial effects can cause the decision you make about one stimulus to influence your decision about a subsequent stimulus (Akaishi et al., 2014; Treisman & Williams, 1984). These effects may be conflated with serial dependence or could even be the true cause of this effect. This decision-based serial dependence could manifest in several possible ways. Serial effects in decision could reflect direct repetition of responses, or more subtle effects based on the influence of decisions on higher level readout of perceptual information.

Given the close relationship between perception of a stimulus and decisions about that stimulus, separating perceptual and decision effects may seem difficult. Experimental and analysis techniques have been used to try to tease apart the validity of these explanations with some studies suggesting that decisions, rather than stimuli, are the main driver of serial dependence (Fritsche et al., 2017; Pascucci et al., 2019). However, some experimental paradigms may be open to interpretation. In addition, recent evidence suggests that while serial dependence could be driven by decisions, it may still generate perceptual change (Fornaciai & Park, 2022; Pascucci et al., 2019).

The initial work of Fischer and Whitney did address the possibility of decision effects explaining serial dependence (J. Fischer & Whitney, 2014). A two alternative forced choice experiment was used to rule this out. Participants were asked to reproduce an orientation before being asked which of two subsequently presented stimuli was tilted further clockwise. The latter task was used to measure the presence of a change in perception after the initial orientation decision. If serial dependence was not a result of attraction between decisions, but instead produced a genuine perceptual change, then observer responses to stimuli in the perceptual comparison task should reflect this. Serial dependence might alter perception of a subsequent stimulus at the same location, and this would be evident in its perceived relationship to the comparison stimulus (more/less clockwise). The authors concluded such a perceptual change was evident, suggesting that serial dependence was not merely a decision effect.

However, Fritsche et al. (2017) were the first to provide evidence for decision-based serial dependence using a similar task to the earlier work of Fischer and Whitney. In a replication of the Fischer and Whitney experiment (Fischer and Whitney, N = 3, Fritsche et al., N = 25), Fritsche et al. found a repulsive serial effect. A subsequent variation of this task based on perceptual equality rather than comparison (discussed below) also demonstrated a repulsive effect (N = 24). Fritsche et al. (2017) also used an adjustment task, which produced a positive effect consistent with the earlier results of Fisher and Whitney (2014). Fritsche et al. used these results to argue that positive serial dependence arises from non-perceptual processes, such as attraction between decisions, whereas negative serial dependence was perceptual in origin.

Cicchini et al. (2017) found positive serial dependence using a modified version of the 2AFC procedure used by Fritsche et al. with smaller orientation differences and range (N = 16). This experiment used the same equality judgement as Fritsche et al., limiting the influence of decision biases. The authors also looked at dependencies between responses in the adjustment portion of the procedure, finding that there was a serial effect between them, despite the fact that they were separated by the comparison task. This was taken to suggest that decision level factors can influence adjustment tasks. In this case the authors arrived at the conclusion that perceptual and decision factors contribute to positive serial dependence. These conflicting results from very similar tasks have spawned a variety of different methods and analysis techniques designed to differentiate between perceptual and non-perceptual contributions to serial dependence.

1.1.2.2.1. Decision Effects Which Might Account for Serial Dependence.

A number of decision-based effects in the literature might have the potential to account for serial dependence. Simpler decision effects such as straightforward response repetition can be differentiated from serial dependence through analysis. For example, when assessing serial dependence through shifts in the point of subjective equality (PSE) of a psychometric function (J. Fischer & Whitney, 2014). Perceptual effects can cause horizontal shifts; the point at which participants cannot distinguish between two perceptual options genuinely moves to a different point on the stimulus range. On the other hand, response repetition would cause a vertical shift of the function; participants are just more likely to respond one way or the other overall due to a decision bias (Murai & Whitney, 2021). Other decision-based sequential effects could produce more nuanced effects on the PSE, which more resemble the effects of serial dependence (R. M. Gallagher et al., 2019). For example, some decision-based sequential effects may be more prevalent when successive stimuli are similar, as opposed to a uniform probability of repetition across the stimulus range (Akaishi et al., 2014). In this case diagnosing the cause of any perceptual effect based on PSE shifts may be more complex.

Earlier work investigating sequential effects in decisions has proposed mechanisms which might account for serial dependence. Treisman and Williams (1984) suggest that serial effects may be based on a criterion setting mechanism. In this theory “Tracking” shifts criteria away from the most recent response, producing assimilative response repetition. This operates according to a rationale which has also been proposed for serial dependence; recent observations are likely to be similar to current ones (J. Fischer & Whitney, 2014). Therefore, after observing a specific stimulus the threshold of information required for an unsure observer to report seeing the same stimulus should be lowered, as the stimulus is still likely to be there. This can result in a repetition of the previous decision in binary decisions. This explanation has been applied to the related phenomenon of confirmation bias (Hsu & Wu, 2020). However, Tong and Dubé (2021) note that a limitation of criterion-setting is that it typically applies to binary or Likert-like decisions. Using frameworks to extend this to continuous stimuli (Kvam, 2019) might allow this sort of model to also account for serial dependence observed in non-binary decisions.

Another, more recently described example of a decision process producing assimilative responses is decision inertia, which can operate in sequential perceptual judgements similar to those used in serial dependence experiments (Akaishi et al., 2014). This idea is based on a model where the brain uses decisions as a form of feedback on an initial estimate of the decision to be made. This is used to inform the next decision estimate. This can lead to subsequent decision estimates becoming biased by the previous choice, particularly in circumstances where sensory evidence is weak and choice feedback is more informative. This biasing can then lead to sequential effects.

The proposed benefits of decision inertia are similar to those for serial dependence. Luu and Stocker (2018) suggest that a self-consistency principle in perceptual decision making, where previous decisions are assumed by the observer to be correct and used to inform current choices, can improve performance in the face of internal noise generated in working memory representations. This may be consistent with improvements in performance associated with serial dependence suggested by Cicchini and Burr (2018). Inertia in decisions could also act to reduce indecisiveness in the face of ambiguity (Bronfman et al., 2015).

Pascucci et al. (2019) formed an account of serial dependence based on decision inertia. The authors compared the performance of a gain model, as used in the low-level account of Fischer and Whitney (2014), to a “two-process” model, where serial biases instead result from a later decision stage affecting the readout from lower-level units. In this model the perceptual channels described in the Fischer and Whitney models are not subject to a positive change in responsivity after prior stimulation, instead the effect of prior stimulation may produce a repulsive perceptual effect. However, after the initial low-level perceptual response, a trace of the previous decision affects the weight given to each perceptual unit by a top-down processing mechanism.

Earlier work by Jazayeri and Movshon (2007) describes a similar process. The authors suggest that perceptual illusions can arise from task-dependent decoding strategies which alter perception downstream of sensory encoding neurons. In the case of serial dependence, specific tasks might result in patterns of decoding which persist across trials (Trapp et al., 2021). In contrast to the models of Fischer and Whitney, this process would produce serial effects after the initial encoding stage of perception.

In the two-process model of Pascucci et al., the stimulus characteristics decoded from the previous decision would be favoured, giving greater weight to the activity of perceptual units with corresponding preferences. The idea is that as these units were informative in the recent past, they are still likely to be providing useful information. The extra weight given to incoming perceptual evidence resembling the previous stimulus can produce an assimilative effect. This change in weight is dependent on the requirement for a response and does not result from simple stimulus exposure alone. As a result, this two-process model was determined to better capture serial dependence when serial effects are observed to correlate with prior responses/decisions rather than with previous stimuli themselves (Pascucci et al., 2019).

While analysis and modelling techniques have the potential to disentangle separate sources of sequential effects, a better approach might be to design experiments which rule out decision factors in the first place. This is not trivial, and a number of approaches have been applied, some of which may hold up better under scrutiny than others.

1.1.2.2.2. No-Response Trials

Several approaches have been taken to try to rule out the influence of decision effects in serial dependence. Pascucci et al. (2019) employed no-response trials, where observers passively observe stimuli with no decision requirement, to isolate the effect of previous decisions in an adjustment task. Using explicit signalling (the response bar was replaced by a black disk) of no-response trials, Pascucci et al. report a lack of attractive serial effects in the absence of a perceptual decision. When attractive effects did occur, they were shown to be dictated by the previous decision, even after a series of no response trials. This was taken as evidence for a decision basis to serial dependence.

Rather than communicating to participants that no response was required, previous studies showing assimilative effects from no-response trials simply did not present a post-stimulus response screen (Czoschke et al., 2019; J. Fischer & Whitney, 2014; Liberman et al., 2014; Manassi et al., 2017; Xia et al., 2016). Pascucci et al. argue that if no-response trials are used in serial dependence studies, participants must be explicitly informed, by way of a cue (the post-stimulus black disk in the experiments of Pascucci et al.), that no response is necessary. Without explicit instruction perceptual decisions could still be made in anticipation of the response screen.

Other authors have argued that post-stimulus signalling that no response is required demands a perceptual decision. Kondo and Watanabe (2011) used a similar procedure to Pascucci et al. to isolate the effect of internal evaluation without the demand for a perceptual report, finding that internal evaluation could contribute to sequential effects. In this study, a post-stimulus sound on random trials indicated when a perceptual report was required, forcing participants to evaluate all stimuli in anticipation of this potential cue. This implicit decision behaviour has been suggested to account for results which use post-stimulus cueing of no-response trials (Kim & Alais, 2021).

Nevertheless, similar experimental paradigms have produced results indicating that explicit decisions may be necessary to produce assimilative effects. Bae and Luck (2020) required participants to attend to two stimulus dimensions (direction and colour) before reporting one of them. Importantly, participants did not know which they would have to report until the stimulus had already been observed, necessitating encoding of both stimulus features. In this case the required report of a feature, rather than stimulus encoding, was found to produce a serial dependence effect; if information was not used in the previous trial its assimilative effect in the current trial was reduced or eliminated. The authors found repulsion from the previous stimulus and attraction to the previous response.

Mixed results from post-cued no-response trials might be resolved by modifying experimental procedures. In a serial dependence experiment with a post-stimulus cue, a perceptual decision may still occur. Using a pre-stimulus cue that no response is required could avoid this problem (Suárez-Pinilla et al., 2018). One caveat of pre-trial cues is that they may also reduce working memory representations. Lacking a relevant task, there is less incentive to retain an internal representation of a stimulus. As suggested by Bae and Luck (2020), precues may limit sensory encoding. This renders the content of working memory across trials unclear making it hard to isolate distinct decision and working memory influences (see below) on serial dependence.

Even without cueing, Lau and Maus (2019) argue that the expectation of a specific, repetitive task could cause perceptual judgements on no-response trials in serial dependence experiments. This could affect stimulus encoding as participants expect to perform the same judgement and become accustomed to this, even on trials where no response is required. In addition, explicitly telling an observer not to make a perceptual decision might cause them to do just that. Luu and Stocker (2018) suggest that the results of their experiment indicate that observers implicitly performed a discrimination task on trials where they were not asked to. This fits with the idea of ironic process theory, where asking a participant not to think of something causes them to do so. Wegner et al. (1987) famously demonstrated that asking participants not to think of a white bear inevitably caused them to think of a white bear. In addition, asking participants to ignore stimuli could also conceivably impact observer attention (Sadil et al., 2021). This may create a confound as attention is a key requirement for serial dependence (J. Fischer & Whitney, 2014). Ambiguities in the processing taking place during no-response trials may limit how useful they can be in elucidating the role of decision processes in serial dependence.

However, it may still be possible to draw some conclusions from no-response trials. Authors such as Pasucci et al. (2019) and Motala et al. (2020) included previous stimulus as a factor in analyses, demonstrating that, in the absence of a response on the previous trial, the previous stimulus was predictive of a repulsive effect. This suggests that positive serial effects only arise in the presence of a decision. This is supported by similar analysis techniques applied to trials which did include observer responses. Sadil et al. (2021) used a "split-half" analysis to try to factor out the effects of previous decisions and previous stimuli. Errors constitute a difference between stimulus and response; larger errors represent a greater divergence from stimulus values. By separating responses based on the scale of error in the previous trial, the authors were able to look at whether the current response more closely resembled the previous stimulus or the previous response. In their analysis the authors found that previous stimuli exert a repulsive response while previous responses have an attractive effect. Similar results were also obtained by Morimoto and Makioka (2022), who suggested that the appearance of attractive effects from prior stimuli actually reflects the correlation between prior stimulus and response. This allows the attractive effect of response to mask repulsive effects from prior stimuli.

1.1.2.2.3. Other Experimental Approaches

Although implicit decisions are an issue for no-response tasks, other techniques may be able to circumvent this problem. In their experiments investigating ironic process theory, Wegner et al. (1987) showed that asking participants to think of something else limited white bear thoughts. This suggests that using a distractor task rather than a no-response task might be a way to limit perceptual decisions.

Following this sort of logic, multiple studies have used alternating decision tasks where observers make decisions about two different stimulus dimensions to dissociate decision and perception. Asking observers to alternate between two different tasks on the same type of stimulus means that decisions made on one trial are irrelevant to the decision made on the following trial. Therefore, any serial effect observed may be due to perceptual aspects of the previous trial rather than a carryover of decisions. Lau and Maus (2019) alternated orientation and audio judgements in multimodal stimuli. The authors concluded that even with an orthogonal task, or with no task, stimulus appearance alone can cause serial dependence in orientation, providing evidence for the low-level perceptual view of serial dependence.

One concern with alternating judgements is that implicit decisions may still occur. Fritsche et al. (2019) used alternating orientation/size judgements, demonstrating serial dependence of orientation even across size judgements. However, serial biases in orientation were noticeably lower when size was attended to rather than orientation. A potential problem with this approach is that it was not possible to rule out participants paying some attention to the orientation of stimuli on size judgement trials, meaning that implicit judgements could still occur. As with no-response tasks, pre-cueing the required response might reduce implicit decisions. In an experiment with pre-cued decision types, Suárez-Pinilla et al. (2018) found that, in contrast to an uncued no-response task, pre-cued alternating judgements eliminated serial dependence.

Although many experiments are designed to minimise implicit decisions, other work has suggested that implicit judgement may be inconsequential for serial dependence. Van der Burg et al. (2019) used an alternating task in gender/attractiveness decisions. In this case rapid, implicit judgements were assumed to occur, based on previous work (Ritchie et al., 2017). The authors report that although implicit attractiveness judgements likely occurred, assimilative effects were not evident when the previous decision was made on gender rather than attractiveness, suggesting that an explicit decision is required for serial dependence as opposed to just perception. This would seem to be in agreement with the experiments of Bae and Luck (2020), where only explicit decisions produced assimilation.

However, issues with alternating tasks other than the role of implicit judgements may also need to be considered. Pegors et al. (2015) alternated attractiveness and hair darkness judgements, finding that stimuli produced a contrastive effect whereas decisions were assimilative.Chang et al. (2017) argue that this switching between subjective and objective judgements might cause participants to not maintain their criteria for one judgement type across a different judgement. Switching between decision types may therefore come with ambiguities which hinder interpretation.

Tasks involving adjustment stimuli, either no response or alternating judgements, may also be logically unsound for detecting perceptual effects. The “El Greco” effect refers to the way in which perceptual distortions should affect both test and adjustment stimuli (Anstis, 2002). If serial dependence causes a perceptual change, this same perceptual change might be expected to also apply to any adjustment stimulus used to report the experimental stimulus. If serial dependence caused a 45° stimulus to appear as 50° then the adjustment stimulus should be similarly affected; the participant reports 45° while believing they have reported 50°. Perceptual effects would be undetectable in this task due to equal influence of any perceptual illusion on both test and adjustment stimuli. If serial dependence was observed, it could only be a non-perceptual effect. This argument applies only if serial dependence equally affects adjustment stimuli, something which may be prevented in experiments where experimental and adjustment stimuli are sufficiently different (Cicchini et al., 2017; Fritsche et al., 2017; Samaha & Postle, 2017). In addition, other experiments have looked for evidence of perceptual changes in serial dependence occurring in tasks where the stimulus dimension of interest is not explicitly reported in the task.

Tasks where the decision made is orthogonal to the stimulus dimension of interest have been used to assess the impact of decisions on serial effects. Fritsche et al. (2017) used an equivalency judgement where the orientation of the stimulus was not explicitly the focus of the task, dissociating responses and decisions from stimulus values (Schneider & Komlos, 2008). A two-alternative forced-choice paradigm was used, and participants were asked to judge whether two on screen stimuli featured the same orientation or not rather than directly reporting stimulus orientation. In this case the authors found a repulsive effect of previous stimulus. However, a later replication by Cicchini et al. (2017) using a wider range of stimulus values found attractive effects at small orientation differences.

It has been argued that 2AFC may be the superior methodology when investigating perceptual illusions (Morgan et al., 2013). Morgan et al. (2013) argue that, when dealing with perceptual illusions, it makes theoretical sense to prefer an AFC procedure over the method of adjustment, as it is easier to avoid the decision strategies which can mimic true sensory effects. Spatial 2AFC tasks may also be less vulnerable to post-perceptual processes, allowing a more direct measure of perception compared to adjustment tasks (J. Fischer & Whitney, 2014; Fritsche et al., 2017), which rely on memory of the presented stimulus (This may also be a weakness of two interval forced choice tasks, as used by Liberman et al., 2014).

2AFC tasks measure serial dependence as a shift in the PSE of a psychometric function. Although in some cases the shift in PSE may look identical for perceptual and decision-based effects, other measures may allow decision and perceptual effects to be teased apart. Gallagher et al. (2019) showed that the point in the stimulus range at which observers lack confidence can indicate where their perceptions are most ambiguous. A shift in this point of low confidence can hint at genuine perceptual change despite similarities in PSE. For example, Observers might find it difficult to determine if a 67.5° stimulus is orientated closer to 45° or 90°. However, if their perception was suddenly altered so that all orientations looked like they were 15° further clockwise, the 67.5° stimulus would now look more like 82.5°. This decision is much less ambiguous. Meanwhile a stimulus that was 52.5° pre-perceptual shift would now look like 67.5°. The objective stimulus value which the participant perceives as ambiguous has shifted and we would also expect a corresponding shift in their confidence; 52.5° should now be associated with low confidence. Alternatively, if perception is unaffected but a shift in decision making has occurred then the point at which participants are least confident should not shift. Similar shifts in PSE could occur in both cases but shifts in confidence should be restricted to perceptual changes. Applying this technique to a serial dependence task, Gallagher et al. (2019) found that 1-back serial effects can arise from genuine perceptual change. However, it was also found that 2-back serial effect were likely to arise from a decision bias. This may suggest that both perceptual and decision factors can contribute to serial dependence.

Other experiments have followed a similar approach to Fritsche et al. (2017), using tasks where observers do not directly report the feature of interest. Rafiei et al. (2021) used an odd one out task followed by an adjustment response querying stimulus orientation. The authors argue that implicit orientation decisions were unlikely in the odd one out task, as the explicit decision being made on each trial concerned the location of an odd stimulus rather than a choice about its features. It was therefore concluded that a decision effect could not account for observed serial dependence in orientation judgements. However, the argument of Lau and Maus (2019), that the expectation of an adjustment task could cause implicit orientation judgements, may still apply.

A later experiment by Collins (2020) demonstrated a positive serial dependence in a task where the response of the participant was orthogonal to stimulus appearance. Participants were required to determine whether or not a specified Gabor differed in orientation from the rest of an array of Gabors stimuli; effectively the same sort of judgement as the equality task used by Fritsche et al. (2017). The location of the potential oddball remained the same on each trial whereas the position of distractors changed. The change in position of distractors was intended to limit their susceptibility to serial dependence. Serial dependence between trials could reduce the number of "oddball present" responses by masking the difference between oddball and distractor stimuli when prior and current stimuli at the oddball location were of similar orientation. So an oddball orientation of 45° amongst an array of 50° Gabors might be missed if the orientation of the previous stimulus at the same location as the oddball was within the range of serial dependence (prior orientation of 45-65°). An assimilative bias from the previous oddball location Gabor could cause the oddball to look more like the distractor Gabor stimuli. Conversely, on trials where the oddball location Gabor is not actually an oddball, serial dependence at that location could cause the non-oddball to look different from distractor Gabors, causing an erroneous "oddball present" response. Due to the changing locations of distractor stimuli, we would not expect them to be similarly affected by serial dependence.

This task required no reproduction of orientation, only recognition of an odd stimulus. It was found that serial dependence from the orientation observed on the previous trial could hide an odd orientation. Serial dependence also prompted oddball responses on non-oddball trials. These results were taken as evidence that stimulus appearance was altered despite the lack of any explicit decision regarding stimulus orientation (Collins, 2020). It could be argued that detecting an odd orientation required an implicit perceptual decision on both oddball location and distractor stimuli but this stretches the idea of perceptual decisions into something which is hard to differentiate from passive perception (Liberman et al., 2016).

Other experimental paradigms have used orthogonal tasks which do not directly involve perceptual decisions about stimulus characteristics which may be subject to serial dependence. Murai and Whitney (2021) used a detection task where participants noted the presence or absence of a Gabor in a white noise image. This resembled the detection tasks used in hysteresis experiments; participants reported the presence of a stimulus when no stimulus was present. The crucial takeaway from this experiment is that detection was influenced by the orientation of the previous stimulus. For trials where no Gabor was present, participants more readily reported a Gabor when the white noise image contained orientation information similar to the orientation of a prior high contrast inducer Gabor. While orientation and spatial frequency would set a Gabor stimulus apart from a pure noise stimulus, the orientation of the Gabor was irrelevant to the observer's decision in this case as they were only asked to detect stimuli, not report their character. Thus, the task-irrelevant stimulus orientation produced a perceptual effect on the following trial based on stimulus similarity (distinguishing this outcome from a simple response time change typical of priming). While an implicit orientation judgement could produce a similar result (operating under something like the weighted decoding scheme proposed by Pascucci et al.) this assumes perceptual decisions occurring with no incentive and with little distinction to separate these implicit decisions from passive perception.

Methods incorporating orthogonal tasks may rule out explicit decision making, however as suggested for no-response tasks, implicit decisions could still occur (although with little incentive). Interpreting some serial dependence results in terms of unavoidable decision effects seems to stretch the idea of perceptual decisions. Liberman et al. (2016) suggest that if perceptual decisions are implicit/obligate then there is little distinction between a perceptual decision and ordinary, passive perception. The simpler explanation in cases such as the experiments by Collins, and Murai and Whitney might just be that serial effects can occur without the need for decisions.

1.1.2.2.4. Why Can Decisions Seem to Cause Serial Dependence?

If serial dependence can occur without perceptual decisions, then how can we explain the apparent role of previous decisions found in some tasks? One possibility is that decisions might just better reflect subjective perception of stimuli than objective stimulus values do. If perception does not perfectly correlate with stimuli, then observer responses should reflect this. Any attractive effect to the prior percept would then appear as an attraction to previous response rather than previous stimulus (Sheehan & Serences, 2023).

John-Saaltink et al. (2016) suggest percept rather than stimulus or response as the basis of serial dependence. Investigating trials where observers made incorrect responses, the authors showed that attraction was toward the incorrect response as opposed to the true value of the stimulus. Similar findings were reported by Zhang and Alais (2020) who found comparable levels of positive assimilation to previous choices regardless of accuracy, indicating that participant perception of the stimulus (right or wrong) was the important factor rather than the objective stimulus value. Zhang and Alais broke responses down by previous stimulus or previous response in order to control for the separate influence of both. The authors found no effect of previous stimuli but a positive serial dependence for previous choices, reasoning that the perception of the previous stimulus was causing serial dependence as opposed to the actual previous stimulus. This may be consistent with the results of Ranieri et al. (2022) who suggest that superior decoding of previous response from neural signals as opposed to previous stimulus suggests the better correlation of response with what was actually perceived.

One approach to investigating this issue come from an inversion of typical no-report paradigms, which try to remove the role of decisions. Pascucci et al. (2019) instead sought to remove perceptions rather than decisions. The authors presented pure noise stimuli which featured no obvious orientation. The intention was to see if decisions made in the absence of any clear percept still elicited serial effects. Serial effects were still observed to occur, with this result being taken to demonstrate that serial dependence arises from a decision-based mechanism.

However, a similar experiment by van Geert et al. (2022) reports that assimilative effects are reduced or absent when stimuli which should produce a clear percept are also absent. This was taken to indicate that the reliance on previous decision largely reflects a dependence on previous percept, however decision factors also likely have a role. The obvious barrier to interpretation of both of these experiments is that we do not have a direct measure of observer perception, only an implication of reduced perceptual discriminability. This leaves the conflicting results of these experiments difficult to resolve.

Support for the idea of attraction between percepts comes from an experiment manipulating participant perception. Taking advantage of the “surround tilt illusion” Cicchini et al. (2021)

tested the influence of previous perception on subsequent perception. It was found that illusory information, rather than objective stimulus values, determined the extent of serial dependence. In this case the authors suggest that reliance on perception means that serial dependence is the result of high-level influences.

Recent evidence from studies which attempt to directly manipulate the content of conscious awareness also suggests that perception is a requirement for serial dependence. Fornaciai and Park (2019a) used backwards masking to demonstrate that awareness of a stimulus was necessary to induce serial dependence. Kim et al. (2020) report similar findings using binocular rivalry to induce switching between perceptions before observing the effect of conscious and non-conscious stimuli on serial dependence.

1.1.2.2.5. Does Attention Account for the Apparent Role of Decisions?

If percept is the focal point of serial dependence, that still leaves the issue of how to explain the apparent lack of assimilative effects in some no-response tasks (Pascucci et al., 2019). Perception has still occurred in this case although decisions have not. This may point to additional necessary factors correlated with both decisions and perception, such as attention. In an investigation of serial dependence, Fornaciai (2021) observed carry over of information from the previous trial in neural activity. The authors found that this carry over was weaker in the absence of an explicit task, suggesting that while tasks are not necessary for this carryover, attention or more general task related processes might enhance this process.

The role of attention in assimilative serial dependence is well established (Fornaciai & Park, 2018; Liberman et al., 2014). Fischer and Whitney (2014) demonstrated that cued stimuli at different locations exert a serial dependence effect whereas uncued stimuli at the same retinal location do not. Decisions might be associated with a focussing of covert attention which is not necessarily present in the absence of a decision requirement. Alternatively, decisions might facilitate carryover of attention between trials. Either way, the reason decisions might sometimes appear to be necessary for serial dependence is due an accompanying focussing of attention.

Akaishi et al. (2014) proposed that, in the case of decision inertia, attention could be drawn to a particular stimulus feature, such as orientation information, and this biasing of attention to that feature might then carry over to the next stimulus observed. Akaishi et al. tested this possibility by cueing participants to report the orientation of either red or green overlaid moving dot patterns. Decision inertia was reported despite a shift in attention from one dot pattern colour to the other. However, while attention to either red or green dots was manipulated, observers still attended to the same feature of these dots, suggesting that a carryover of attention to specific stimulus features might remain. A similar idea has been suggested to account for confirmation bias in perceptual decisions. Talluri et al. (2018) suggest confirmation bias arises from selective deployment of attention following a prior decision. In both cases, attention on a trial may be biased by the prior trial.

If this also applies to serial dependence, lack of a decision may be associated with an absence of attention to a stimulus feature, perhaps reducing any assimilative bias (Suárez-Pinilla et al., 2018). Evidence does suggest that attending to stimuli produces assimilative effects whereas ignoring stimuli does not and may even produce repulsive effects (J. Fischer & Whitney, 2014; Rafiei et al., 2021). Fritsche and de Lange (2019) report that attended features of a stimulus exhibit serial dependence whereas unattended features of the same stimulus do not. Multiple other studies report similar results, with serial dependence limited to the stimulus dimension which was relevant in the previous stimulus (Feigin et al., 2021; Togoli et al., 2021; Van der Burg et al., 2019). This could imply that when attention is diverted to a different stimulus feature, serial dependence is reduced.

Fornaciai et al. (2019b) suggest that differential focussing of attention might also account for differences in serial dependence observed across different tasks. Adjustment tasks might result in more focussed attention on a specific stimulus feature whereas other tasks, such as those involving comparison between stimuli, might instead result in a broader form of attention. While this biasing of attention could also happen during passive perception, decisions may have a focussing effect which ensures covert attention is drawn to a specific stimulus feature. In some circumstances attention might still be captured during passive perception, resulting in serial dependence in the absence of a decision. Ongoing task relevance might drive attention to specific stimulus features even in the absence of a response requirement on prior stimulus features (Togoli et al., 2021) as suggested by the argument of Lau and Maus (2019) that repetitive tasks create the expectation of making a decision.

However, the procedures of some studies might limit the possibility of diminished covert attention. Pascucci et al. (2019) used a post-stimulus no-response cue, observing reduced serial dependence. Similarly, Bae and Luck (2020) used a post-stimulus cue to indicate which stimulus dimension was to be reported, finding no serial dependence from stimulus features which were not reported in the prior trial. As discussed above, post-stimulus cueing may necessitate encoding of all stimulus features and this should require attention to those features. These results might suggest that the roles of perception and attention may not be able to fully explain the role of decisions in serial dependence. Future experiments should explore the role of covert attention in serial dependence more directly.

1.1.2.2.6. Does Serial Dependence Produce Perceptual Change?

While there are competing explanations for serial dependence, the terms and viewpoints expressed in this debate may be contentious in themselves. Although many of the above studies refer to serial dependence as either a perceptual or post-perceptual effect, the difference between these two explanations is not always clear. Fornaciai and Park (2018) state the difference between perceptual and post-perceptual explanations as a difference in phenomenal representations; a perceptual origin suggests that phenomenology is altered whereas a post-perceptual explanation entails that the perception is the same, serial effects only being expressed in decisions or behaviour (for discussion of this distinction see Storrs, 2015).

Pascucci et al. (2019) frame the debate differently by suggesting that, regardless of its origin, serial dependence could produce alterations in stimulus appearance. In this account, serial dependence arises from a decision-related process but still causes stimuli to look different to the observer; serial dependence effects may not arise from the earliest levels of sensory encoding but can cause differences in phenomenology. The authors suggest that previous decisions represent the sensory channels which have been most informative in the immediate past, promoting perceptual continuity. Similarly, Cicchini et al. (2021) propose that serial dependence is a post-perceptual effect which feeds back to early sensory areas to alter perceived stimulus appearance. This was characterised by Fornaciai and Park (2021) as a “prior” generated by higher-level brain regions which feeds back to lower-level visual areas. This acknowledgement of the possibility of perceptual change differs from earlier accounts of decision-based serial effects which specifically rejected the possibility of perceptual change (Treisman & Williams, 1984).

The role of prior decisions in serial dependence remains ambiguous. Recent experiments do demonstrate a dependence of serial dependence on the previous response rather than the previous stimulus, with stimuli in fact exerting a repulsive effect (Fritsche et al., 2017; Moon & Kwon, 2022; Pascucci et al., 2019; Sadil et al., 2021; Sheehan & Serences, 2023; Zhang & Luo, 2023). This could be taken to indicate an attractive effect occurring between decisions rather than attraction to prior perception. However, dependence on response might represent an observer’s subjective perception of objective stimulus features. Other results allow for the possibility of a genuine change in perception as a result of serial dependence (Cicchini et al., 2017; Collins, 2020; J. Fischer & Whitney, 2014; Murai & Whitney, 2021). This doesn't rule out decision based serial dependence as it remains possible that a decision-based effect could have a subsequent influence on perception. However, in some cases experimental procedures arguably rule out decision biases accounting for observed serial effects.

1.1.2.3. Working Memory

Memory is another important candidate mechanism proposed to underlie non-perceptual serial dependence. The key difference with this interpretation is that instead of producing perceptual changes, serial stimulus presentation might actually cause distortions in the memory of a stimulus before a response is made (Fritsche et al., 2017). Perceptual and memory changes may be hard to distinguish because studies demonstrating serial dependence typically ask participants to respond to stimuli a short time after they have appeared. This means that a response suggesting a misperception could indicate that the stimulus was genuinely perceived differently, or it could show that the observer's memory of the stimulus was corrupted in some way prior to the response. Fritsche et al. (2017) suggest that serial dependence may arise from a biasing of working memory representations towards previous perceptual decisions, rather than being an effect which occurs at the time of perception.

Although the differences between interpretations of serial dependence may sometimes seem trivial, the role of memory has implications for the nature and role of serial dependence. If serial dependence operates in working memory rather than perceptual systems then this would allow it to work alongside sensory systems devoted to change detection, rather than in opposition to them (Bliss et al., 2017). This idea might even be compatible with other explanations; the apparent role of decision effects could actually be attributable to decisions enhancing the transfer of information into working memory (Motala et al., 2020).

Reframing serial dependence in this way leads to further considerations which are relevant to the nature of this effect. Different types of memory content could be responsible for serial dependence. A vivid internal representation of stimuli could be retained, or something more abstract, like the memory of which decision was made about a stimulus. Furthermore, whatever the content of this memory, it could be held in ongoing activity, or it could be something more like an impression which is reactivated later.

Before considering these implications, it is worth looking at whether there is evidence of memory being a major factor in serial dependence. Several features of serial dependence do suggest a relationship with working memory, including the role of attention (J. Fischer & Whitney, 2014), something believe to be intimately linked with working memory (Bliss et al., 2017). The reduction of serial dependence with greater time between stimulus presentation and report is also suggestive of a memory decay component (Bliss et al., 2017). A number of studies have probed the contribution of memory and provide evidence that it may be involved in positive serial dependence (Czoschke et al., 2019; Fornaciai & Park, 2020b; Fritsche et al., 2017; G. Mei et al., 2019).

In their study demonstrating serial dependence in orientation reproduction, Fischer and Whitney (2014) ran a control experiment to test the possibility of memory involvement. On a quarter of trials, after reproducing the orientation of the displayed stimulus, participants were asked about the orientation of the stimulus presented one or two trials previously. Participants were at chance in determining whether the orientation of the earlier stimulus was right or left of vertical. This suggests that active memory representations of prior stimuli are not necessary for serial dependence to affect current stimuli.

However, Fritsche and colleagues (2017) argue that adjustment tasks used to study serial dependence rely on recollection of the current stimulus rather than directly measuring perception. To test the role of memory, Fritsche et al. varied the length of time between viewing a stimulus and demanding a decision, forcing participants to retain the viewed stimulus in working memory for different durations prior to a response. The authors reasoned that an observed increase in serial dependence after a longer delay occurred due to prolonged retention of information in working memory, allowing more time for biasing of memory representations (similar findings are reported by Ellinghaus et al., 2019 and; Stein et al., 2020). Similarly, Bliss et al. (2017) came to the conclusion that attractive serial dependence can only occur with a delay period between presentation and response requirement. During this delay, working memory can be drawn towards previous stimuli, although at greater delay lengths (>6s) serial dependence is reduced as memory decays.

However, in contrast to the studies cited above, Manassi et al. (2018) found that serial dependence can occur without a delay period before a perceptual judgement. The authors concluded that while memory may modulate serial dependence, there remains a perceptual component. Several experiments investigating serial dependence in attractiveness judgements report similar results with no delay period (Chang et al., 2017; Kramer & Jones, 2020; Kramer & Pustelnik, 2021). Manassi et al. showed that serial dependence appeared with lower contrast stimuli, suggesting that the strength of serial dependence might be linked more generally to stimulus uncertainty. This idea has been corroborated by other experiments directly measuring the impact of uncertainty in the current stimulus (Ceylan et al., 2021; G. K. Gallagher & Benton, 2022 - included as Chapter 2 of this thesis). This has further been taken to suggest that delays between stimulus and response may induce uncertainty, promoting serial dependence (Sheehan & Serences, 2022).

Other experimental approaches have also been argued to rule out memory contributions. Detection tasks, which involve noting the presence of a stimulus rather than reproducing its character, arguably reduce the involvement of working memory for stimulus features. In this case participants do not reproduce a previously viewed stimulus, they just note whether a target was present, no rehearsal or retrieval of stimulus features is necessary (Murai & Whitney, 2021). Experiments using techniques not based on stimulus reproduction, such as detection or oddball tasks, have demonstrated serial dependence, suggesting that memorising specific stimulus features is not necessary for this effect to occur (Collins, 2020; Murai & Whitney, 2021; Rafiei et al., 2021). Additionally, memory of the specific decision made would not appear to be responsible for serial dependence in this case as the decision is orthogonal to the stimulus features which are being affected.

Some experiments do report working memory effects such as increased serial dependence with longer memory retention of stimuli. Mei et al. (2019) report enhanced serial dependence when the time between two stimuli was greater. However, this experiment used a two-interval forced choice procedure where two successive stimuli appeared before an observer was asked to select one of them. This task naturally demands an explicit representation of both stimuli be held in working memory. Similarly, Fornaciai and Park (2020b) demonstrated assimilative effects between memorised stimuli. Three stimuli were presented in succession before one stimulus was cued for report. The authors found the typical pattern of serial dependence where reports of one stimulus were biased towards prior stimuli.

It is important to note that the procedures of both of these experiments required memorisation of stimuli. The attractive effect between memory representations in these tasks may not be applicable to other tasks where memory requirements are minimised. However, it is entirely possible that serial effects can be implemented at multiple levels of cognition. Memory based serial effects could operate at the same time as serial biases which do not recruit working memory.

1.1.2.3.1. Repulsive Memory Effects, Attractive Decision Effects?

If we do accept the idea that serial dependence can be a memory effect, another issue raised by this interpretation concerns the content of memory. Is serial dependence reliant on memory of the stimulus itself or just of the decision made regarding that stimulus? Multiple authors have sought to distinguish between phenomenogical/sensory memory and decision memory influences on sequential effects. Lages and Treisman (2010) make the distinction between memory traces (pictorial representations of stimuli) and decision traces (essentially a quantitative record based on stimulus parameters which affects the decision criterion on subsequent trials). While not necessarily following this specific definition, Fritsche et al. (2017) describe serial dependence as a product of memories of previous decisions. A description which may be more compatible with recent research suggesting that the content of working memory may be more abstract and task-centric (Kwak & Curtis, 2022).

Given that decision effects (see “Decision Effects” above) have also been proposed as an explanation for serial dependence, Pascucci et al. (2019) carried out an experiment designed to distinguish between the influence of working memory content and previous decisions on serial dependence. Participants were asked to memorise several stimuli presented simultaneously before one of these stimuli was cued for report. This procedure was designed to load working memory with new information on each trial, erasing any working memory representations from the previous trial. In this case working memory content was in fact found to exert a repulsive effect, in opposition to the typical outcome of attractive serial dependence. In contrast, previous decision exhibited an attractive effect typical of serial dependence. The strong implication here is that serial dependence is based on prior decisions rather than memory representations of previous stimuli.

Earlier experiments, not necessarily designed to answer this question, provide similar results. Similar results are reported by Czoschke et al. (2019). The procedure used by Czoschke et al.

resembled the methodology of Pascucci et al. Observers saw two consecutive stimuli in each trial before one was cued for report. Retro-cueing stimuli required memorisation of both as participants did not know which would be queried. A perceptual decision was only taken at the end of each trial whereas working memory content was updated within each trial. The previous decision was therefore carried across trials, whereas consecutive memory representations were not, making the cross-trial effect compatible with the decision effect identified by Pascucci et al. Notably the last stimulus to be observed only exerted an attractive effect across trials if it was also retro cued for report. This implies that a decision was necessary for serial dependence.

The authors also observed repulsive effects within trials alongside attractive effects across trials. The repulsive effect found within trials was interpreted as a case of repulsion existing between representations held in working memory. This repulsion may act to segregate concurrently task relevant items whereas attraction integrates previously relevant material (Czoschke et al., 2019). A similar idea was expressed by Bae and Luck (2017) in speculating on the contrast between their experiments (which used a similar procedure to Czoschke et al.) and those of Fischer and Whitney. Bae and Luck explicitly required memorisation of stimuli and observed repulsion between similarly oriented Gabor stimuli. The authors proposed that this repulsion enhanced differentiation between very similar stimuli. Rather than causing attractive serial dependence, working memory representations appear to exhibit repulsive effects which enable them to remain distinct.

In contrast to repulsive effects between memory representations, the attractive effect between trials found by Czoschke et al. (2019) likely operates at a different level of processing as it relies on an explicit or implicit decision (Czoschke et al., 2020). These results, as well as those of Pascucci et al., suggest that attractive effects are a result of a quantitative record of the decision made rather than the actual representational content of working memory.

On the other hand, some studies characterise memory interference as arising from interactions between memories of visual content, without an explicit decision. Fornaciai and Park (2020b) produced results suggesting that an attractive serial effect could occur between memory representations of stimuli. Three stimuli were sequentially presented before one of these stimuli was cued for report. Post-trial cueing was used to ensure memory representations were formed for all stimuli rather than just the test stimulus. This procedure was designed to test if an assimilative serial effect was capable of operating based on memory representations. Attractive effects were observed between successively presented stimuli. Interestingly, the authors demonstrated that the effect operated in forward and backward directions; the memory representation of the first stimulus in the sequence altered the report of the second and the representation of the second similarly influenced the first. In this case an attractive effect is even being exerted by items in working memory which were viewed after target stimuli. This suggests that serial dependence could be the product of a larger process of memory conflation.

Fornaciai and Park did not find a serial effect across trials. Given that decisions were made at the end of a sequence of stimuli in this study, such a cross-trial effect would be predicted by an account based on perceptual decisions. Lack of a cross-trial effect suggests that, in this case, decisions were not producing assimilation. In addition, the stimulus for report was cued after all stimuli had been observed. This means that all stimuli must be encoded in working memory rather than just the target. This procedure demands individuation between three stimuli and hence should have promoted a repulsive bias according to the conclusions of Czoschke et al (2019). Attractive effects occurring within trials instead point to an assimilative serial dependence reliant on working memory representations of stimuli.

1.1.2.3.2. Active Maintenance or Reactivation Of Memory?

Disagreements about the role of memory in serial dependence extend beyond memory content. Although "working memory" might suggest an active representational process maintained by the persistent firing of cortical neurons, previous stimuli could also produce a more passive effect, such as an alteration in synaptic storage, which could maintain information in the absence of persistent neural activity.

Active processes were suggested to be responsible for assimilative serial effects (likened to proactive interference) by Papadimitriou et al. (2015) The authors found that an observed biasing effect towards previous stimuli could be modelled by the bump attractor model of cortical representations. The bump attractor consists of a network of neurons, tuned to continuous features of visual space, such as orientation. Strong reciprocal excitatory connections between neurons representing neighbouring areas of visual space can cause maintenance of neural activity after stimulation, while broader inhibition between more distant neurons prevents widespread activation, these two features promote a stable attractor state which can persist over time. This reverberation means that a "bump" of persistent network activity can continue even after stimuli have been withdrawn. This allows representations to be sustained during the delay period of a trial, in a neural activity-based code (Wimmer et al., 2014) as opposed to the more passive mechanism of synaptic changes, which instead produces changes in subsequent neural activity. To use an analogy - if passive synaptic changes are like writing down a phone number to be read later, the bump attractor is like repeating the number aloud until it is dialled. This ongoing neural activity/reverberation could cause attractive serial dependence by interfering with the encoding of subsequent stimuli. A persistent signal from the previous stimulus might influence the current stimulus signal to be similar. Luo and Collins (2023) found a trace of previous stimuli in ongoing neural signals, arguing that this suggested that serial dependence is the result of active neural representations rather than synaptic changes.

Alternatively, positive serial dependence may rely on an interplay between passive and active mechanisms. Bliss and D'Esposito (2017) proposed a hybrid model, with contributions from both ongoing activity and passive effects. This model included a role for ongoing neural activity, again using a bump attractor, as well as activity-silent mechanisms, such as changes to synapses. This model relies on the activity of NMDA receptors in prefrontal cortex (Bliss & D'Esposito, 2017). This may be clinically relevant as reduced serial dependence has been found in individuals with conditions which affect NMDA receptors and modifications to this model may simulate this deficit (Eckert et al., 2023; Stein et al., 2020). This model also included a role for more passive processes. Modifying the bump attractor to include augmentation from synaptic plasticity permitted the model to simulate the time course of serial dependence, where any attractive effect between stimuli decays with time (Bliss & D'Esposito, 2017).

This cooperative interplay between active memory processes and passive effects is also emphasised in work by Barbosa et al. (2020) with persistent activity arising from bump attractor dynamics which fades between trials but is then reactivated from activity silent mechanisms. The authors found that previous stimuli could not be decoded from EEG data during the middle of an inter-trial interval, however above-chance decoding was possible before the start of the next trial. This gap in sustained signal implies reactivation from activity-silent mechanisms (an idea supported by Fornaciai & Park, 2020a; Ranieri et al., 2022; Stein et al., 2020; Zhang & Luo, 2023) rather than an uninterrupted active process (Luo & Collins, 2023). Subsequent sensory activity may cause the imprint of previous activity to produce an "echo" of past stimuli, producing an attractive effect. The work of De Azevedo Neto and Bartels (2021) has also been interpreted as supporting the activity silent view. Weak transcranial magnetic stimulation (TMS) was shown to enhance serial dependence, while strong TMS was shown to eliminate it. This was taken to mean that increases in activity stimulated existing synaptic connections. When general strong TMS is applied it wipes out any specificity in synaptic storage, effectively returning it to baseline. This mixture of results from different studies suggests that both passive and active memory processes may contribute to serial dependence.

1.1.2.3.3. Multiple Systems?

Assuming a role for memory in serial dependence. It remains unclear whether serial dependence involves a combination of perceptual, decision, and memory systems. Serial dependence clearly involves some trace of the previous stimulus, which we might be inclined to call memory, but conflicting results from delay experiments leave it unclear if perception, or memory, is the driving force behind this effect. Although nothing rules out multiple independent sources of assimilative serial bas. It also remains ambiguous exactly what sort of memory content might be involved in serial dependence. Some of the above results imply that this effect is dependent on memory of a decision rather than a true internal representation of a prior stimulus. Additionally, how this memory is maintained in neural activity is ambiguous but both active and passive memory mechanisms may have a role in producing attractive serial effects.

Ideally, procedures should be adopted which isolate the contribution of memory effects in serial dependence to distinguish their influence from other potential causal factors, such as decision inertia or perceptual effects. However, this may be difficult in cases where manipulations, such as pre-trial cueing of required responses (Suárez-Pinilla et al., 2018), arguably affect both perceptual decisions and working memory content (Bae & Luck, 2020).

1.1.2.4. Evidence from Imaging Studies

Imaging studies have probed the neural basis of serial dependence effects and offer some ideas about their perceptual or post-perceptual origins. St. John-Saaltink et al. (2016) found that serial dependence manifests in early perceptual areas such as V1. This study used multi-voxel pattern analysis to look at distinct patterns associated with different perceptions. The authors observed that orientation signals present in V1 were biased to previously seen stimuli.

These results from visual cortex could be taken as evidence for the view that serial dependence effects are perceptual in nature, however it is not completely clear that localising serial dependence to a brain region associated with perception rules out top-down influences upon that region (Pascucci et al., 2019). Kok et al. (2016) demonstrated that activation of visual cortex can occur due to top-down influences, showing that deep cortical layers of V1 are selectively affected. The authors suggest this differs from typical bottom-up activation which should activate all cortical layers, being more pronounced in middle and superficial layers. Previous work by Kok et al. (2012) demonstrated a "sharpening" of representations in visual cortex based on top-down expectations, in a predictive coding model. These studies highlight the complex relationship between top-down and bottom-up processing, especially when considering effects on phenomenology/perception.

In contrast to the early perceptual area account, work by Schwiedrzik et al. (2018) suggests that pre-frontal cortex could be responsible for serial dependence effects. In this case, serial dependence was described as a perceptual memory effect. This study used direct intracranial recordings in a sample of six epilepsy patients and suggested that dorso-medial prefrontal cortex (dmPFC) has a role in perceptual stabilisation. Pre-frontal areas are associated with decision-based processes as well as sensory processes (Euston et al., 2012), although this assumption does not necessarily confirm a decisional basis for serial dependence. The closely related phenomenon of perceptual hysteresis (described above) has been suggested to arise from activity in higher visual and fronto-parietal regions (Schwiedrzik et al., 2014). Notably the authors used a diffusion model of decision making in their study which suggested that hysteresis effects arise from genuine perceptual, rather than decisional, processes.

Fornaciai et al. (2021) suggest that a complex feedback process could be occurring during sequential stimulus responses. Using EEG, the authors found that information from the previous trial can be decoded on the current trial, suggesting the possibility that this information might produce a perceptual smoothing effect. However, behavioural serial dependence may reflect a top-down influence upon responses. To clarify this distinction; it was found that various stimulus features could be decoded from neural activity, however serial dependence evident in responses only occurred for stimulus features relevant to the task. This task relevance as well as the role of processes such as attention and memory were argued to suggest that serial dependence arises from top-down processing.

Van bergen and Jehee (2019) found that stimulus representations can be decoded in visual cortex and carry with them a degree of uncertainty, which is predictive of the strength of serial dependence. When uncertainty in prior stimuli was high, serial dependence was reduced. These findings imply a Bayesian pattern of responses in serial dependence. The authors suggest that this process could operate based on readout of uncertainty present in sensory signals at a post-perceptual stage of processing. However, the authors note that assimilation between visual representations at early processing stages was not ruled out.

Other neuroimaging results suggest further complexity in this process. Hajonides et al. (2023) suggest that only repulsive biases can be decoded in early visual areas despite behavioural results showing assimilate effects. This is consistent with work by Sheehan and Serences which suggests that early visual areas demonstrate repulsive effects which are later compensated for by higher areas, resulting in serial dependence.

Taken as a whole, what these neuroimaging studies might suggest is that early, low-level repulsive biases give way to attractive biases produced by top-down feedback from higher level brain areas. Fornaciai et al. (2021) note that serial dependence has been shown to cross stimulus types, as in the example of orientation serial dependence crossing from static Gabor stimuli to dynamic dot motion patterns (Ceylan et al., 2021) suggestive of a higher level basis to this effect. However, signatures of serial dependence in occipital cortex observed by Fornaciai et al. might therefore reflect the site of action of serial dependence rather than its origin; serial dependence may be a high-level effect which causes changes in early perceptual areas (Fornaciai, 2021). Similarly, Ranieri et al. (2022) suggest that the signals of serial dependence may be localised mainly in occipitoparietal cortex, indicating that it does act directly on current perception.

1.1.3. Repulsive Serial Effects

The basis of negative effects is less controversial than positive serial dependence. Multiple studies (Fritsche et al., 2017; Pascucci et al., 2019; Roseboom, 2019) attribute negative serial dependence to adaptation in cases where stimulus differences are small. Fischer and Whitney (2014) did note that positive serial dependence can be overridden by stimulus exposure times sufficient to produce perceptual adaptation. This suggests a natural time course of positive serial dependence gradually declining towards adaptation with prolonged stimulus exposure. Fornaciai and Park (2019a) used masking to eliminate positive serial dependence and determined that in the absence of attractive effects, adaptation dominates and arises even from very brief stimulus exposure.

Notably there are two forms of repulsion observed in serial dependence studies. While some studies report repulsive effects, in an inversion of positive serial dependence (Bae & Luck, 2017; Fritsche et al., 2017), negative effects can also arise from extreme stimulus manipulations. Fischer and Whitney (2014) demonstrated that stimuli which are beyond a specific range of the previous stimulus will not be susceptible to assimilative effect (for orientation, >60° difference, Fritsche et al., 2017). In this case, repulsion dominates perception producing commonly observed “peripheral bumps” (Bliss et al., 2017). Moon and Kwon (2022) suggest that the reversal of sequential effects at large stimulus differences arises from the repulsive effect of previous stimuli operating over a larger range of stimulus values than the attractive effect of decisions. Repulsion from previous stimuli may therefore occur beyond the range of any attractive effect from previous decisions.

Fritsche et al. (2017) left the origin of repulsive effects observed with large sequential differences open, suggesting that further work is needed to determine whether they arise from a perceptual or decision process. Fritsche and deLange (2019) showed that this repulsive effect was not due to feature-based attention, unlike positive serial dependence. Repulsion at large orientation differences was suggested to be retinotopic, but possibly distinct from adaptation.

Where positive and negative serial effect exist concurrently, a common interpretation is that negative serial effects, where current perception is repelled away from the previous percept, are perceptual, whereas positive serial dependence is a post-perceptual process (Fritsche et al., 2017). Pegors et al. (2015) serves as a useful example of this view. This study identified positive and negative serial effects in attractiveness ratings. Positive effects were claimed to be due to a response bias whereby current responses are attracted towards previous responses. Negative effects were stated to arise from a perceptual mechanism as demonstrated by the fact that this effect could be enhanced with increased stimulus duration, a feature of perceptual adaptation. Similarly, Suárez-Pinilla et al. (2018) showed negative effects appearing across different tasks within the same experiment, whereas concurrent positive serials effects were dependent on the type of decision made previously. This was taken to suggest that the negative effects were more likely to be perceptual adaptation effects, as opposed to the decision-based nature of positive effects. Repulsive effects found in a working-memory based numerosity task were also thought to arise from adaptation (Valsecchi et al., 2018).

1.2. Flexibility in Serial Dependence

Authors such as Fischer and Whitney have suggested that serial dependence may be useful in maintaining perceptual stability. However, certain stimuli and conditions can cause variation in the extent of this effect. Additionally, there may be variation among individuals (Bliss et al., 2017; Collins, 2021; Kondo et al., 2022). Some observers exhibit weaker positive serial dependence and others even show negative serial effects (Bliss et al., 2017; Fornaciai & Park, 2019b; Fritsche et al., 2017). This may reflect differences in the weighting of positive serial dependence and simultaneous repulsive effects (Zhang & Alais, 2020). Notably, there are circumstances where we might expect serial dependence to be regulated depending on its utility.

Ideally, serial dependence should only occur in conditions where it makes sense to rely on previous experience. Kiyonaga et al. (2017) use the term “context-dependent flexibility” to describe the way in which serial dependence should be regulated in certain situations. If differentiation of perception is required, or the signal-to-noise ratio of stimuli is unfavourable (Cicchini et al., 2018), then serial dependence may not be optimal, and any weight given to recent perception should be reduced. If spatial or semantic features indicate the persistent relevance of recent information, then the weight given to this information should be increased. Serial dependence should operate in the proper context in order to maintain an accurate representation of the environment.

Stimulus-specific behavioural expectations may moderate serial dependence. For example, Taubert and Alais (2016) found variation in the application of assimilative sequential effects in face stimuli based on the likelihood of face-specific stimulus changes. Faces were rotated around different axes and rated for attractiveness. Assimilative effects were found to occur in sequentially presented stimuli which were rotated side to side around the face (yaw axis rotation) but not for those which were flipped upside-down between trials (roll axis rotation). Serial dependence was still found in yaw axis rotation of upside-down faces indicating that it was not simply the difficulty of processing upside down faces which prevented assimilation. The authors suggest that these results arise because changes in the yaw axis are more biologically plausible; it is common to see the side of someone's face but unlikely that you will see it upside down. Sequential effects in attractiveness have also been suggested to vary with consistency of perceived gender and race (Kramer et al., 2013). Familiarity with face stimuli has also been shown to dictate the strength of serial dependence (R. Kok et al., 2017). These results suggest specific ways in which serial dependence may be regulated by features specific to stimulus type.

Temporal reliability may also create a context which favours serial dependence. Some stimuli may be more subject to positive serial dependence, based on a tendency to remain stable over time. In the case of face stimuli, perceived gender could be more subject to positive serial dependence, as gender does not vary within an individual face, however expressions, being more dynamic, may be more subject to negative effects (Taubert et al., 2016). This is because repulsive serial effects, where perception is pushed away from previous stimuli, serve to enhance sensitivity to meaningful changes in expression.

This seemingly straightforward idea is not free from debate. Liberman (2018) suggests that there may in fact be a maintenance of emotional expression via positive serial dependence, a result supported by other studies (Alais et al., 2021; G. Mei et al., 2019). Similarly, eye gaze direction has been found to be subject to positive serial dependence (Alais et al., 2018) despite change sensitivity potentially being valuable in this domain (D'Entremont et al., 2007).

Stability could also be something which acts against serial dependence. Alais et al. (2018) argue that head position may be more stable than eye movements. This was argued to mean that a repulsive effect in sequential viewing of head position would therefore be optimal; if you think you might have seen a head movement, you probably have, as head position does not actually change that often. Similarly, negative serial effects in orientation arise from extreme stimulus changes (J. Fischer & Whitney, 2014; Fritsche et al., 2017). Extreme changes are less likely to be due to noise, so the noise-masking effect of serial dependence is therefore not optimal.

In contrast to the stability of head position, eye position is subject to constant insignificant changes due to microsaccades. This means that a positive serial dependence may be optimal to avoid registering every small eye movement as a true, sustained change in eye position. Incorporating the probability of any perceptual instability into the application of serial dependence could avoid "overfitting" perception to noise (Alais et al., 2018).

Some experiments do explore the role of stimulus stability in serial dependence. In a test of the impact of variability on a "recency bias" effect, Gordon et al. (2019) manipulated the probability of correlation between successive stimuli in a detection task and found that the observed recency bias was not sensitive to the expected change in stimuli. This task resembled the sort of detection task used for the phenomenon of hysteresis; an effect closely related to serial dependence (see "Hysteresis" above). However, it is possible that tasks based on changes in stimuli rather than stimulus presence might produce different results.

Pasucci and Plomp (2021) found that serial dependence was reduced for a sequence of stimuli which followed a predictable rotation pattern as opposed to random sequences of orientations. In this case the regular rotation implied that the next stimulus in a sequence would be rotated away from the previous whereas the random sequence did not suggest this predictable difference. In this case the reduction in serial dependence was due to the antagonistic effects of representational momentum. Abreo et al. (2023) produced a similar result, suggesting that while serial dependence may be applied to random stimulus sequences, predictable stimulus changes can instead cause repulsion.

Differences in the strength of serial effects may also be based on the reliability of stimuli. Serial dependence involves the combining of past and present stimulus information in a way that may be beneficial in perceptual decisions (Cicchini et al., 2018). To really be useful this process should also take into account the reliability of stimulus information (Cicchini et al., 2018). It doesn’t make sense to incorporate information which is highly uncertain. Furthermore, the relative uncertainty of both past and present stimuli should be considered. It makes sense to leverage past information if current data are unreliable and hence serial dependence should occur. On the other hand, if the previous data were noisy and current data are clearer, the previous data should probably be disregarded; serial dependence is not useful in this scenario (van Bergen & Jehee, 2019). If serial dependence demonstrated such a responsiveness to uncertainty, it could mean that this process conforms to Bayesian-like principles.

1.3. Is Serial Dependence a Bayesian Process?

Changes in the magnitude of serial dependence under different circumstances might be able to tell us something about the logic underlying this effect. Maybe serial dependence is useful in some situations but less so in others. On the face of it, serial dependence produces errors in judgement. This raises the question of under which circumstances this bias might be beneficial?

Despite producing apparent misperceptions, serial dependence has been suggested as a mechanism which smooths over meaningless noise in sensory signals (Burr & Cicchini, 2014; J. Fischer & Whitney, 2014). Following this logic, serial dependence has been modelled using the Kalman filter, an algorithm which can reduce noise in a signal by combining variable estimates with a prediction from previous data (Kalman, 1960). A Kalman filter gives more weight to current input when the squared difference between current and prior stimuli is large, resembling the effects of serial dependence as described by Fischer and Whitney (2014). This means that minor changes in input are treated as noise in the signal to be down-weighted and smoothed over. In contrast, large differences between past and present input are attributed to genuine, meaningful change in the environment. In this case current input is given greater weight allowing it to override predictions based on prior input. The system is thereby able to smooth out noise while retaining sensitivity to change (Burr & Cicchini, 2014). Burr and Cicchini (2014) showed that serial dependence, modelled as a Kalman filter, can improve accuracy despite producing apparent misperceptions.

Under circumstances where the probability distributions associated with stimuli are Gaussian, the Kalman filter constitutes a Bayesian approach to perception, where estimates of sensory uncertainty are incorporated into current predictions. The concept of perception as a Bayesian process is well established in the literature (Knill & Pouget, 2004). The basic idea is that to make optimal inferences about the likely source of sensory signals, the brain should take into account the reliability of those signals (Geisler & Kersten, 2002). Prior beliefs are modelled as a probability distribution. This is combined with another distribution representing the likelihood of incoming sensory signals to produce a reasonable estimate of the state of the environment. This estimate then serves as a prior for the next sequence of inference. This process has been suggested as a source of sequential dependencies in perception (Glasauer, 2019). In this case, perceptual attraction to the recent past occurs because previous perception fills the role of a prior belief about the sensory environment influencing current perceptual inference.

For the Bayesian inference explanation to make sense, serial dependence should be responsive to the level of uncertainty associated with stimuli. It might make sense to rely on previous perception when current sensory information is ambiguous. However, incorporating prior stimuli into current perception is not optimal from a Bayesian perspective if the current stimulus is more reliable (Cicchini et al., 2018).

Some experimental evidence does suggest that serial dependence conforms to these expectations. Cicchini et al. (2018) demonstrated that serial dependence appears to be reduced when stimuli are unreliable. Further to this van Bergen and Jehee (2019) showed that viewing stimuli perceived as more reliable followed by less reliable stimuli enhanced serial dependence while viewing unreliable stimuli followed by more reliable stimuli reduced serial dependence.

Results such as these have led to numerous plausible variations on Bayesian models which have been suggested to account for serial dependence. Some models complement Bayesian inference with realistic assumptions about the environment. For example, the Bayesian model of Van Bergen and Jehee (2019) also included a model of natural temporal statistics, which allowed it to take into account the scale of the difference between current and previous stimuli.

Kalm and Norris (2018) compared a number of Bayesian models of serial dependence including models incorporating environmental statistics and models sampling over longer timescales. The authors conclude that a model which resembled the Kalman filter, but which incorporated weighted information from multiple past states, best captures serial dependence.

A typical Kalman filter only implicitly includes information prior to t-1, whereas this modified filter explicitly used information from further back in time, assigning specific weights to different time points. The Fidelity-based integration model constructed by Tong and Dubé (2021) uses a similar weighting of current and recent stimuli without being explicitly Bayesian. This model uses a recency-weighted moving average which may be computationally cheaper than a full Bayesian approach. Both models show that weighting recent information from several timepoints allows for correlations in visual environments over time, taking into account recency, rather than just from the immediately preceding stimulus.

Following this same logic, Fritsche et al. (2020) constructed a Bayesian ideal observer model which used data from multiple previous timepoints, weighted by their recency. In order to also model commonly observed repulsive biases, Fritsche et al. expanded on this approach with the addition of an ‘efficient encoding’ component. This mechanism allocates perceptual encoding resources according to likely upcoming stimuli predicted by the visual system, with the aim of maximising the mutual information between prediction and resources. What this means is that the representation of stimuli resembling previous input becomes more precise, with a corresponding loss of precision in less similar stimuli. Where the representation of each possible stimulus is used to construct a likelihood function, this results in an asymmetry. When convolved with the prior distribution, this asymmetric likelihood function can produce a posterior distribution which is skewed away from the previous stimulus. This results in repulsive biases from recent stimuli which allow the visual system to maintain sensitivity to change. Combining this ‘efficient encoding’ mechanism with weighted Bayesian decoding reproduced the short-term attraction and long-term repulsion often observed in studies of serial dependence. Results from Yu and Ying (2021) also suggest that a similar mechanism might account for a reduction in serial dependence for stimuli which are familiar (R. Kok et al., 2017).

Bayesian models have been a popular way of modelling serial dependence and some studies do support this characterisation. Cicchini et al. (2018) and van Bergen and Jehee (2019) both produced results arguably showing the effect of stimulus reliability on serial dependence. Similarly, confidence has been suggested as another measure of uncertainty which might be a component in Bayesian models of serial dependence. Partial evidence has been found for this interpretation with several studies finding that high confidence (low subjective uncertainty) in the prior trial can enhance serial dependence (Bosch et al., 2020; Samaha et al., 2019; Suárez-Pinilla et al., 2018).

However, recent evidence suggests problems with the Bayesian conception of serial dependence. Ceylan et al. (2021) found that serial dependence did not respond to the reliability of stimuli in a way that was predicted by Bayesian inference (nor by the fidelity-based integration model of Tong and Dubé). In this study the authors looked at all possible transitions between low and high uncertainty stimuli. Serial dependence was found to be unresponsive to uncertainty in the prior stimulus. Only uncertainty in the current stimulus dictated the strength of the effect. Previous work demonstrating an apparent Bayesian dimension to serial dependence could also be interpreted the same way. Ceylan et al. observe that the work of Cicchini et al. (2018) was limited to transitions between stimuli of similar levels of uncertainty (i.e. low to low uncertainty and high to high uncertainty) while van Bergen and Jehee (2019) only looked at transitions between different levels of uncertainty (low to high uncertainty and high to low uncertainty). This means that it is possible that only the level of uncertainty associated with the current stimulus was affecting serial dependence in both experiments. The level of reliability of the previous stimulus did not influence serial dependence, contrary to the Bayesian narrative. The influence of objective reliability in the current trial (Ceylan et al., 2021; G. K. Gallagher & Benton, 2022 - see Chapter 2), and subjective confidence in the prior trial (Samaha et al., 2019; Suárez-Pinilla et al., 2018), might suggest that some combination of different measures of uncertainty might enable a Bayesian mechanism in serial dependence. Nevertheless, as of the time of writing no complete evidence for this combination of stimulus uncertainty and confidence in serial dependence exists.

However, it is also possible that effects of previous stimuli could be washed out by other Bayesian factors. The models of van Bergen and Jehee (2019) and Fritsche (2020) Incorporated the probability of change of stimuli. In random stimulus sequences the high probability of stimulus change might be enough to wash out any uncertainty dependent modulation of serial dependence (notably in the above results serial dependence does not disappear completely, potentially suggesting some low baseline level of reliance on the previous stimulus). On the other hand, Pascucci and Plomp (2021) and Abreo et al. (2023) suggest that random sequences promote serial dependence as opposed to predictable rotational sequences.

1.4. Conclusions

Outstanding questions concern the origin of serial dependence; to what extent is it a perceptual or post-perceptual effect? Serial dependence could be an effect which causes stimulus perception to be attracted towards the previous stimulus. Alternatively, it could just be a tendency to repeat similar decisions. It could also be a tendency to repeat the previous decision, which then has some influence on perception of the current stimulus, or even a combination of perceptual and non-perceptual factors. The specific role of memory is also unclear; serial dependence might be a change in perception, or it could just change in the memory of a stimulus. The origins of serial dependence remain ambiguous with evidence for different mechanisms. Alternative explanations come with their own complications which may not fit the observed data perfectly.

If serial dependence is a computationally efficient way to smooth over visual noise (Burr & Cicchini, 2014; J. Fischer & Whitney, 2014) it might make sense to incorporate it into perceptual inference at an early stage of processing to reduce the propagation of redundant information further up the perceptual decision hierarchy. Kuang (2019) notes that if a bias is introduced at an early perceptual stage, it would be expected to also affect later processing stages such as memory or decision processes. In this case additional post-perceptual implementations of this process could cause errors to be compounded. The apparent antagonism between serial dependence and repulsive effects arising from adaptation might function to reduce compounding of errors arising from a general attractive tendency across cognitive and perceptual processes.

Furthermore, a universal low-level implementation might prevent flexible responses to different classes of stimuli. It has been hypothesised that context-dependent flexibility should alter the strength of serial dependence in situations where it might not be useful (Kiyonaga et al., 2017). Differences in facial expression or identity which could be less prone to serial dependence (Taubert et al., 2016) might not be differentiated by a low-level process. Additionally, existing low-level perceptual processes such as adaptation might be acting in opposition to a perceptual implementation of serial dependence. In this case a two-process mechanism as described by Pascucci et al. (2019) or Fritsche et al. (2020) might make more sense.

Although multiple competing explanations for serial dependence have been proposed, it is not clear that they are incompatible. The pressure to maintain stable perception in the face of noise could act to produce equivalent outcomes in perception, decision and memory. Some authors have suggested that this may be beneficial. If serial dependence operates in working memory rather than perceptual systems then this would allow it to work alongside sensory systems devoted to change detection, rather than in opposition to them (Bliss et al., 2017).

Nevertheless, it remains unclear at what level serial dependence is occurring. Although it many cases post-perceptual accounts appear to provide a better model of observed data, other experiments suggest that genuine perceptual change has occurred (Cicchini et al., 2017; Collins, 2020). Pascucci et al. (2019) propose that serial dependence could be a post-perceptual effect which produces changes in perception. This is a very interesting idea which would have implications beyond studies of serial dependence (Firestone & Scholl, 2014; Storrs, 2015).

An emerging picture suggests that serial dependence may be a late-acting response-based effect which opposes earlier low-level effects (Fritsche et al., 2017; Gekas et al., 2019; Pascucci et al., 2019). However, it may be that this post-perceptual effect still has an effect on perception via top-down action on early sensory areas, several experiments suggest that observers do experience a perceptual chance (Collins, 2020; Murai & Whitney, 2021).

While serial dependence might be beneficial under certain circumstances, it does produce errors. Serial dependence should therefore be regulated rather than being applied equal all of the time. Ideally, there should be a logical way of determining if serial dependence is permissible in any given situation. As stated above, serial dependence could be the result of a form of Bayesian inference in perception. A hallmark of this would be a sensitivity of serial dependence to uncertainty. A Bayesian process would weight sensory data by their associated reliability in order to determine the contribution that data makes to current perception. Unreliable data should not be incorporated into perception as strongly. If prior data are unreliable, their influence should be down-weighted, resulting in reduced serial dependence.

Conversely, if current data are unreliable, serial dependence from prior stimulus information might be a more favourable outcome.

In this thesis the role of uncertainty in serial dependence will be explored, with the aim of assessing whether it is realistic to suggest that this assimilative bias does operate according to Bayesian principles. Chapter 2 explores this question by using stimuli expressing different levels of noise. This stimulus noise is used to test whether serial dependence integrates previous observations into current perceptual decisions in a way which is optimal from a Bayesian perspective.

The results of Chapter 2 suggest another key question concerning the nature of serial dependence. This assimilative bias could be a perceptual effect or just an attraction between decisions. Chapter 3 investigates the question of whether serial dependence represents an attraction to stimulus or response. The results of Chapter 3 are then used to inform the analysis of data in Chapter 4.

Chapter 4 explores the role of subjective uncertainty by measuring observer confidence in perceptual decisions and how this impacts serial dependence. Subjective confidence might differ from objective stimulus noise in a number of ways, most importantly in arising later in the decision-making process than any effects of objective uncertainty. Importantly, confidence might require a response. This might make confidence a more relevant measure of uncertainty for serial dependence if this bias is an attraction to the prior response rather than the prior stimulus.

Chapter 2. Current Stimulus Uncertainty Predicts Serial Dependence in Orientation Judgements

2.1. Introduction

The prevalence of serial dependence across visual categories suggests that it might be a general feature used to stabilise perception against noisy visual input. By “blending” the perception of two very similar stimuli viewed over short timescales, the visual system is relying on expected regularities in the environment to smooth over differences which are likely to be due to noise (J. Fischer & Whitney, 2014). Notably this effect does not occur when stimulus disparities are larger, and change is therefore more likely to reflect meaningful differences in the environment (Burr & Cicchini, 2014; J. Fischer & Whitney, 2014).

Although serial dependence may reflect a strategy to cope with noise in perceptual inference, for optimal perception it should also vary with stimulus reliability (Burr & Cicchini, 2014). Previous perception may be a useful guide for how to interpret current sensory evidence when there is some doubt surrounding what you are seeing, in this case greater weight should be given to prior perception rather than the current evidence (van Bergen & Jehee, 2019). However, if previous perception is less reliable, current evidence should be given more weight, and effects such as serial dependence should be downregulated. This approach approximates a Bayesian perceptual strategy, where estimates are weighted by their relative reliability (de Lange et al., 2018; Kersten et al., 2004; Knill & Pouget, 2004).

Previous research has suggested uncertainty regarding current stimuli can affect serial dependence. Cicchini et al. (2018) manipulated uncertainty by varying the characteristics of Gabor stimuli. Observers generally find judgements of orientation around cardinal axes easier (Girshick et al., 2011). Cicchini et al. found that Gabor stimuli oriented around the cardinal axes, where stimulus uncertainty is lower, produced reduced levels of serial dependence.

Stimulus uncertainty was also manipulated by varying the frequency of Gabor gratings; higher frequency Gabors being taken to be more precise and hence less uncertain. Serial dependence was again found to scale with stimulus uncertainty; presenting observers with low frequency stimuli resulted in a greater tendency towards assimilative responses.

Expanding upon this finding, van Bergen and Jehee (2019) found that the relative level of uncertainty dictated the strength of serial dependence. The authors developed a decoder which used the orientation preferences and correlated noise of voxels in an fMRI image to build up a posterior distribution specifying the probability that any orientation produced the observed pattern of activation on a trial. The width of this posterior distribution quantified the degree of uncertainty, which was also found to correlate with behavioural variability in an orientation reproduction task. This was used to look at the impact of moving between different levels of stimulus uncertainty (*i.e.* high to low and low to high uncertainty). It was found that greater sensory uncertainty in the prior orientation stimulus relative to the current stimulus (as decoded from fMRI) reduced serial dependence whereas reduced uncertainty in the prior enhanced the effect. These results suggest that reliability of the current stimulus may be a factor that determines the strength of serial dependence in a manner consistent with Bayesian principles.

However, other work has produced results which do not fit with this Bayesian narrative. An experiment by Fritsche (2016) manipulated the signal to noise ratio of orientation stimuli in order to directly alter stimulus reliability. The authors examined the transition between stimuli with different noise levels. Their prediction was that serial dependence should be affected by the relative amounts of noise in current and prior stimuli. Their results differed from initial expectations; the transition from high to high noise stimuli resulted in greater serial dependence than the low to high transition. A similar result was also produced, contrary to author expectations, in the face stimuli experiments of Lidström et al. (2019). When previous and current face stimuli were both degraded, serial dependence was enhanced. These results lie in conflict with Bayesian views of serial dependence, which would instead predict that relatively low noise in the prior stimulus should maximally enhance serial dependence.

Other work has also produced mixed results. The experiments of Ceylan et al. (2021) manipulated uncertainty through differences in spatial frequency. Lower spatial frequency was used as a proxy for high uncertainty, in contrast to high spatial frequency stimuli, which are generally associated with lower uncertainty. This work suggested that only uncertainty in the current stimulus affected the strength of serial dependence. This was in opposition to the predictions of a Bayesian ideal observer model which predicts a reduced impact of low frequency prior stimuli. However, the authors note that low spatial frequency (*i.e.* higher uncertainty) stimuli tend to remain more stable across time in naturalistic environments. This may have acted against the predictions of the ideal observer model as this expected stability may also be taken into account when considering the reliability of previous stimuli (van Bergen & Jehee, 2019).

In the current experiment a similar procedure to that of Fritsche et al. was used to investigate the effect on serial dependence of noise in current and prior stimuli. The results of Fritsche et al. were contrary their own predictions. Given this unexpected pattern of results, we chose to collect new data using a sequence of stimulus movement which promoted a sense of continuity between stimuli. This was done in order to enhance serial dependence so that any effect of noise could be better distinguished. This work was undertaken operating under the hypothesis that, according to the predictions of a Bayesian model, serial dependence should be downregulated when a previous stimulus is noisy relative to the current stimulus, and enhanced when it is the current stimulus that is relatively noisy. Instead, we found that while uncertainty does affect serial dependence, this only appeared to apply to the current stimulus.

We found no solid evidence that an attraction to prior orientations was affected by the level of uncertainty associated with the previous stimulus or response.

A truly Bayesian process would incorporate uncertainty in current and previous stimuli. The current results therefore leave the involvement of Bayesian processes unclear. The effect of ambiguity in the present stimulus may be more consistent with established ideas about serial effects based on decision processes (Treisman & Williams, 1984) or a previously described uncertainty-only model, also based on post-perceptual processes (Ceylan et al., 2021; Pascucci et al., 2019).

2.2. Materials and Methods

This study was approved by the Psychological Science School Research Ethics Committee at the University of Bristol.

2.2.1. Participants

20 participants took part in this experiment (ages 19-39, mean = 25.15, standard deviation = 4.91, 15 female, 5 male). All participants provided informed consent and were free to withdraw from testing at any time. Participants were paid £20 for taking part in this study. All participants had normal or corrected-to-normal vision.

2.2.2. Stimuli

Stimuli consisted of circular patches containing orientation information. On each trial stimuli were assigned a random orientation from 0-180 degrees. A pattern of 1/f noise (Field, 1987) was generated by adjusting the Fourier amplitude spectrum of white noise in Fourier space. An orientation filter was then applied to this noise. The width of this filter was specified with a double angled von Mises distribution. The concentration of the von Mises distribution was set to two different levels to produce low noise stimuli (concentration = 4), which consisted primarily of orientation information near the specified random orientation, and high noise stimuli (concentration = 0.5), which included more information from other orientations (see Figure 2.1). These noise levels were chosen based on prior testing on author GG to find a value at which the task was straightforward, and a value at which the task became difficult but not overwhelmingly so. The binary choice task outlined below was used to validate these noise levels. The noise masks used between trials were produced in the same way as the experimental stimuli, but with the concentration of the von Mises function set to 0 in order to produce stimuli with no discernible orientation (the passband of the noise included all possible orientations). Although this carries the risk that participants could in some cases confuse noise masks and high noise orientation stimuli, as the noise masks contain no coherent orientation information this confusion would only impact the perceived noise level of stimuli and not orientation determination. Stimuli and noise patches were contained in a 1.5 degree standard deviation Gaussian envelope.

The response stimulus consisted of two black dots (width ~1 degree visual angle) sitting on opposing poles of the area previously occupied by the orientation stimulus. The position of these dots could be rotated by the participant such that an imagined line connecting the dots would match the orientation of the experimental stimulus (See Figure 2.2 lower row, third panel). The initial orientation of the dots was random.

A white bar at the bottom of the screen indicated progress in each task, increasing in length as trials were completed. Participants were instructed to fixate on a central fixation cross (width 0.25 degrees visual angle) for the duration of each experiment.

Stimuli were presented on a 24-inch VIEWPixx 3D lite monitor (VPixx Technologies) with a resolution of 1920 × 1080 and a refresh rate of 120 Hz. All experimental scripts were created in Matlab 2019b using the Psychophysics Toolbox for MATLAB (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Stimuli were viewed from approximately 57cm in a darkened room.

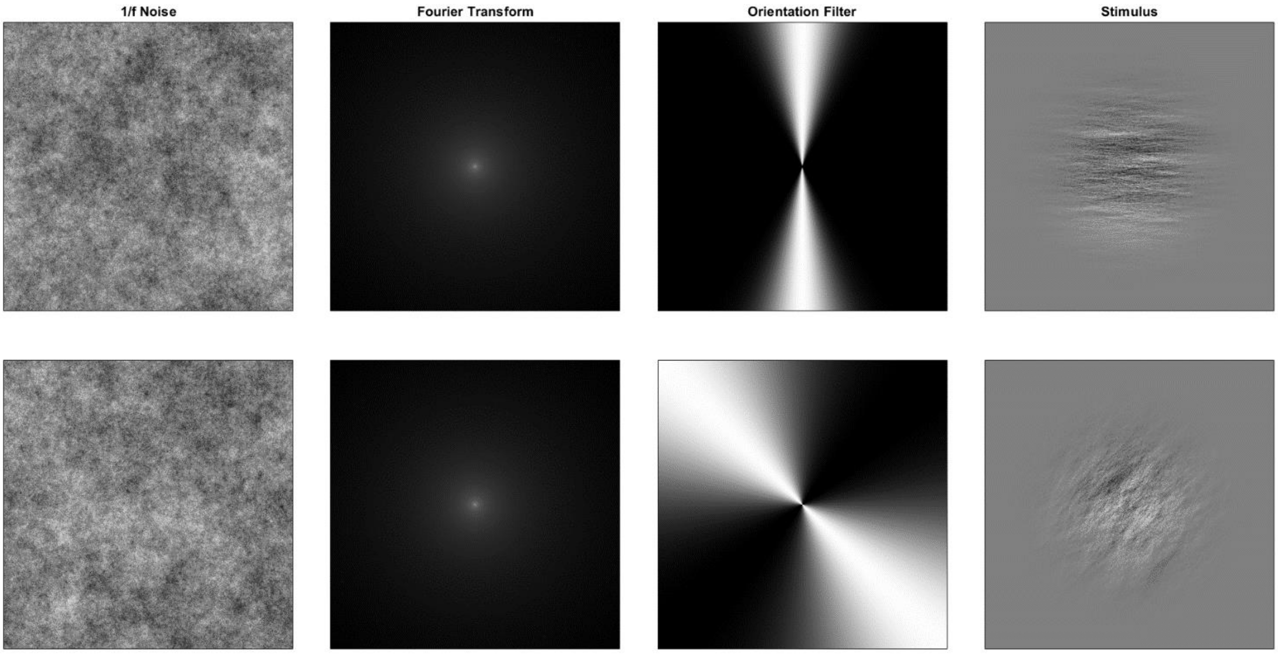

Figure 2.1. Stimulus generation. Leftmost column shows two randomly generated patterns of 1/f noise. These noise patterns were Fourier transformed, as shown in the second column. An orientation filter comprised of two mirrored von Mises distributions was then applied to Fourier-transformed noise. Third column shows two different orientation filters of different orientation and width. Top filter is a 90° filter with concentration parameter value of 4. Lower filter is a 45° filter with concentration parameter value of 0.5. Final column shows the result of reverse Fourier-transforming filtered noise.

2.2.3. Procedure

Participants completed 821 trials of an adjustment task. Each trial presented participants with either a high or low noise stimulus of random orientation, which they were subsequently prompted to reproduce. The noise level of each trial was drawn from a random sequence designed to produce an even number of each noise level transition type (high noise to high noise, low to low, low to high and high to low) over the course of an experimental run.

Each trial followed the same format. First an experimental stimulus was presented for 500ms. This was followed by a noise mask for 1000ms to eliminate visual after-effects. The response stimulus then appeared at the same location. Following a participant response, a grey screen was then displayed for 2000ms before the start of the next trial (trial sequence shown in Figure 2.2). This task took participants around an hour to complete.

Orientation stimuli, noise, and response stimuli appeared at points on a circle of radius nine degrees visual angle which enclosed a central fixation cross (see top panel of Figure 2.2). Each stimulus sequence appeared at a point 45 degrees counterclockwise from the previous stimulus sequence. This circular path of stimuli around the screen was intended to promote serial dependence by providing a consistent object path, which has been shown to favour enhanced serial dependence (Liberman et al., 2016). As noted above, a previous study (Fritsche, 2016) failed to find a relationship between stimuli/conditions which conformed to Bayesian expectations - we reasoned that increasing the signal strength would better allow us to describe any putative effects of uncertainty. Additionally, moving stimuli between spatial positions serves to minimise retinotopic adaptation (Afraz & Cavanagh, 2008).

In another session in the weeks following the initial task, participants additionally completed a binary choice task. This task was designed to assess accuracy in order to confirm that the manipulation of noise levels did affect participants' ability to determine stimulus orientation. Two blocks of this task were completed. In one block participants saw low noise stimuli and in the other high noise stimuli. Participants were asked to decide whether the stimulus displayed was oriented to the left or the right of an imaginary vertical line bisecting the stimulus. This task resembled the adjustment task in appearance. Participants saw stimuli at random points around the circular path taken by stimuli in the adjustment task (consecutive trials of this task shown in Figure 2.3). Displaying stimuli at random points was intended to minimise serial dependence by producing an inconsistent object path (Liberman et al., 2016). Stimuli stayed on screen until participants made a left or right response. Feedback text indicated correct or incorrect responses before the next stimulus appeared. Participants took around an hour to complete both blocks of the task.

Participants responded using a Microsoft Sidewinder controller. In the adjustment task the shoulder buttons were used to rotate the adjustment stimulus. Buttons on the right-hand side of the controller were used to switch between two rotation speeds and to confirm the angle of rotation in order to move onto the next trial. In the binary choice task, the shoulder buttons were used to indicate a left or right response at which point the current trial ended. Participants were allowed to complete practice trials for each task until they were comfortable with the control scheme and instructions provided. Practice trial data were not included in analysis.

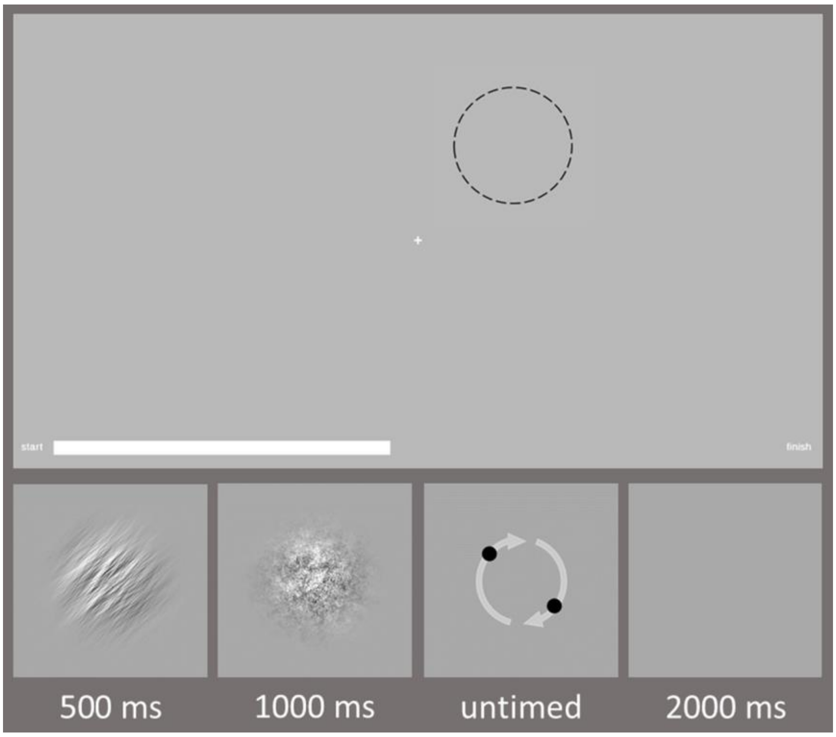

Figure 2.2. Typical trial sequence for the adjustment response portion of the experiment. Top image shows the screen as seen by a participant, stimuli (shown below) appear in the dashed circle. Participants saw a noisy orientation patch for 500 ms, followed by a noise mask for 1000 ms. An adjustment stimulus then appeared onscreen which allowed participants to make untimed responses to the initial stimulus. A grey screen followed the end of each trial and was displayed for 2000 ms. The next trial sequence appeared at a point 45 degrees counterclockwise of the previous trial sequence (dashed circle).

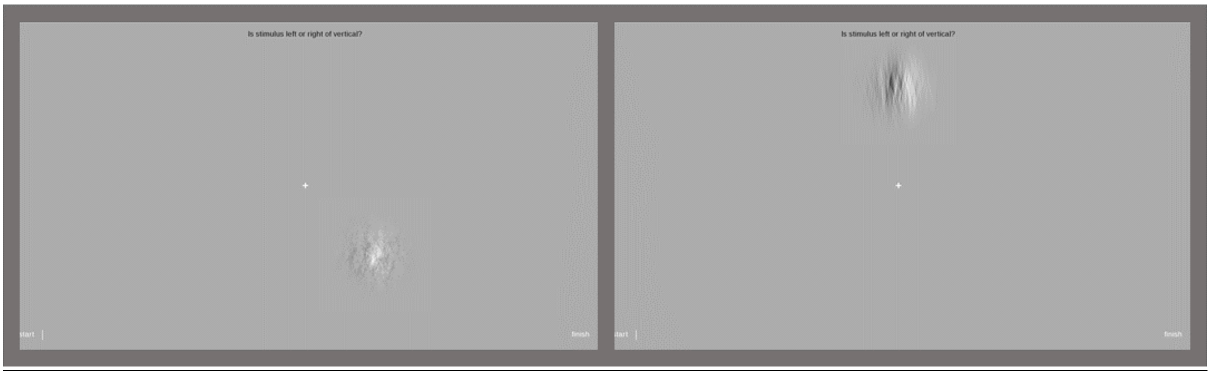

Figure 2.3. Consecutive trials in the binary choice task. Left panel shows a high noise stimulus, right panel shows low noise. Stimuli could appear randomly at any of the eight points (45 degree increments) around the central fixation cross. Stimuli remained onscreen until a response was made.

2.3. Analysis

2.3.1. Binary Choice Task

For each participant, an integral of Gaussian curve was fit using probit analysis (Finney, 1971) to the plot of probability of a clockwise response as a function of stimulus orientation. This procedure was performed for both noise levels. The standard deviation (spread) of this function was taken to indicate sensitivity in participant response, with a high standard deviation indicating that participants found the task difficult.

2.3.2. Main Task

The data gathered from the main adjustment task were subjected to two main forms of analysis. An analysis based on the technique of fitting a derivative of Gaussian curve to the data (J. Fischer & Whitney, 2014) and a “model-free” analysis based on estimating the average bias observed on trials (Samaha et al., 2019). These analyses were applied to investigate the relationship between prior and current orientation perception. The difference between successive trials was calculated in two different ways, being based on either prior stimuli or responses to prior stimuli (outlined below). Both stimulus- and response-contingent data were subjected to model based and model free analyses.

Data were subject to pre-processing to remove non-serial-dependence sources of response bias, in line with previous studies (Fritsche et al., 2017; Pascucci et al., 2019). In order to remove clockwise/counterclockwise response biases, for each participant the circular mean of their response errors was calculated and this was then subtracted from the raw response error data (Fritsche et al., 2017). Errors greater than three standard deviations from the mean error of each participant were removed (Fritsche et al., 2017). This mean error was calculated separately for low and high noise trials. This procedure resulted in an average of 0.76% of trials being removed for each participant.

The extent of serial dependence is thought to be determined by the difference between the stimulus observed on the current trial, and the stimulus perceived on the previous trial (J. Fischer & Whitney, 2014). This can be calculated as the difference between the current stimulus and either the previous stimulus, or the previous response. There should be an association between these values and observer perception of stimuli, but we would never expect this to be a perfect correspondence. However, the relationship between perception and stimulus should be greatly affected by stimulus noise, whereas the relationship between perception and response should not.

We would expect increases in stimulus noise to increase the variability of perception. When viewing a noisy ninety-degree orientation stimulus an observer might respond that it does look like it is oriented at ninety degrees. On viewing another ninety-degree stimulus the observer might decide that this time it looks more like a seventy-degree stimulus and this is again revealed in their response. This variation indicates that the stimulus value itself might not accurately represent the perceived value, and assuming that it does introduces noise into the relationship between current and previous trials.

If we are conditioning on the stimulus as a proxy for the percept, then this measure (the difference between current and previous stimulus) becomes noisier as stimulus noise increases. If serial dependence is some function *f(x)* of the difference between current stimulus and previous percept, and if we can think of the stimulus noise as a Gaussian function *g(x)*, then the resultant observed relationship will be described by the convolution of the two (*g(x) * f(x)*). What this tells us is that, as stimulus noise increases, we would expect the observed function to decrease in amplitude and increase in spread. Assuming that observers are making an honest attempt to report their perception, then taking the response as a measure of perception avoids this problem (Fritsche, 2016). So, in experiments where the focus is on the effect of stimulus variability, conditioning upon previous stimulus is a poor choice; conditioning upon previous response is to be preferred. Studies that have looked at stimulus uncertainty have used both stimulus-contingent (Ceylan et al., 2021) and response-contingent (Fritsche, 2016) approaches. In the present study we performed both stimulus- and response-contingent analyses.

A technique previously used by Pascucci et al. (2019) was implemented in order to avoid the oblique response bias found in this type of response-based analysis (Fritsche, 2016). A sum of sin waves model was fit to the plot of participant errors against orientation (fitting performed using MATLAB ‘fit’ function with ‘Normalize’ = ‘on’ as per the methods of Pascucci et al.). This model was used to capture orientation dependent biases in participant responses. Errors predicted from this model were then removed, leaving data free of orientation-dependent response error. Individual models were fitted for each participant. As uncertainty is known to produce differences in oblique perception (Tomassini et al., 2010), high and low noise trials were modelled separately. Pascucci et al. downweighted errors greater than three standard deviations from the mean, whereas in the current study similar values were removed in the previous stage of processing. This model was applied exclusively to response-contingent analyses. With stimulus-contingent analysis there is a risk that this correction could induce artifacts due to known uncertainty-dependent differences in orientation biases (Tomassini et al., 2010).

2.3.2.1. Model-Based Analysis

A derivative of Gaussian (DoG) curve was fitted to the moving average (window size of 20°) of participant errors conditioned on the difference between current trial and the previous trial (for both stimulus- and response-contingent differences). The DoG curve was identified by Fischer and Whitney (2014) as describing the form of serial dependence. The DoG is defined as follows:

$$y = xawce^{-(wx)^2} + b \qquad (1)$$

Where:

y - participant response error

x - relative orientation of the previous trial

a - amplitude of the curve

w - curve width

c - constant: $\sqrt{2}/e^{-0.5}$.

b - baseline

Parameter a represents the strength and direction of serial dependence, showing the peak response error observed (values reported represent the half amplitude height of the curve from 0). Parameter w describes the stimulus range over which serial dependence is occurring. The value of w was constrained between 0.02 and 0.2.

In line with the analysis methods of Fischer et al. (2014) permutation tests were performed to assess the amplitude of the DoG curve. For a random subset of participants, the sign of the data was flipped and curve fitting was performed on this artificial dataset. This was repeated 10,000 times; *p*-values were calculated by taking the percentage of permutations which produced values of *a* of greater magnitude than the observed value of *a*.

To test the difference between conditions permutation tests were performed on the difference in DoG amplitude in a procedure similar to one employed by Fritsche (2016). For each pairwise comparison, condition labels were randomly swapped within participants and DoG curves were fit to the pooled moving average (moving average window size of 20) of each condition. The amplitude of the DoG curve for one permuted condition was then subtracted from the other. This procedure was repeated 10,000 times. As *p*-values we report the proportion of values in the resulting distribution greater in magnitude than the observed difference.

2.3.2.2. Model-free Analysis

Model-based analyses may produce spurious fits to data. An assumption in fitting the DoG curve is that, outside the range of serial dependence, participant errors fit onto a flat line. This assumption can often be incorrect. The DoG model has previously been observed to produce poor fits to data in the presence of "peripheral bumps", where attractive biases instead become repulsive at large orientation differences (Bliss et al., 2017).

As noted above, a model-free analysis was also applied to our data (Samaha et al., 2019). The median error for each participant was calculated separately for trials where the difference between stimuli was either between 0 and 45 degrees or 0 and -45 degrees. This range, previously identified by Samaha et al., is where we expect to observe serial dependence, while excluding sidebands. The median error value for the negative differences was subtracted from the median for positive differences to produce one value which indicated attractive (positive values) or repulsive (negative values) serial biases for each participant. Bias values were compared using a two-way repeated measures ANOVA to determine the effect of previous and current noise levels as well as their interaction. This model-free analysis was applied to both stimulus- and response-contingent data.

All statistical analyses were carried out in Matlab with the exception of ANOVA which was performed using SPSS.

2.4. Results

Five participants were excluded from the serial dependence analysis due to poor performance. These participants showed a correlation between stimulus and response of less than 0.5, indicating that they were either responding without care, or were finding the task unusually challenging. Participant performance was treated separately for each task; participants excluded from serial dependence task analysis were not necessarily excluded from the binary choice task analysis, and vice versa. Three participants were excluded from analysis of the binary choice task as they produced response values far outside the range of other participants. For these participants the standard deviation (spread) of the fitted cumulative normal was above 60 degrees, whereas those of the remaining participants ranged between 1 and 9 degrees. One other participant was excluded from binary choice analysis for misunderstanding the task.

2.4.1. Binary Choice Task

Performance on the binary choice task confirmed that participants found it more difficult to discern the orientation of the high noise stimulus (standard deviation of cumulative normal = 25.24 for high noise, 4.23 for low noise, significant difference according to permutation test of differences between the two conditions $p < .001$, Cohen's $d = 1.02$). Consistent with these results, participant accuracy was lower for high noise stimuli in the adjustment task (Mean error for high noise stimuli 23.90°, mean error for low noise stimuli 16.22°, $t(19) = 4.57$ $p < .001$, paired t-test, Cohen's $d = 1.02$).

Previous work has used the standard deviation of cumulative Gaussian functions to infer the reliability of stimuli on each trial and determine the extent of serial dependence between any two stimuli according to an ideal observer model (Cicchini et al., 2018). The binary choice task in this experiment was designed to avoid serial dependence effects; stimuli appeared at random points and remained onscreen until a choice was made. In contrast, the adjustment task was open to factors such as post-perceptual effects due to delay periods. Given these differences between the tasks, variability inferred from the binary choice task might not be useful in predicting response variability in the main adjustment task, limiting how useful it can be in extrapolating uncertainty effects on serial dependence. Nevertheless, the binary choice task does suggest that our noise manipulation induced greater uncertainty in participants.

2.4.2. Model-Based Analysis

2.4.2.1. Analysis of the Four Transitions

Stimulus-contingent analysis produced positive amplitude values (see Figures 2.4 and 2.5), consistent with assimilative effects; however the values for high noise and high noise to low were non-significant (Low noise to low noise, $a = 2.14$ degrees, $p = .001$, Root Mean Squared Error = 0.82; High noise to high noise, $a = 2.25$ degrees, $p = .098$, RMSE = 1.27; High noise to Low, $a = 0.98$ degrees, $p = .059$, RMSE = 0.54; Low noise to High, $a = 2.4$ degrees, $p = .006$, RMSE = 0.7). As a form of control analysis, the DoG fitting procedure for stimulus-based analysis was applied to participant errors conditioned on the relationship between orientation in current and future trials (t+1 analysis). No meaningful relationship should be observed, barring precognition. As expected, this analysis produced no significant results (all DoG amplitudes, in all conditions, $p > .10$).

Similarly, response-contingent analysis also yielded positive DoG amplitude values, however in this case all were significant (Low noise to low noise, $a = 1.68$ degrees, $p = .003$, RMSE = 0.56; High noise to high noise, $a = 3.44$ degrees, $p < .001$, RMSE = 0.77; High noise to Low, $a = 1.7$ degrees, $p = .003$, RMSE = 0.43; Low noise to High, $a = 2.59$ degrees, $p = .005$, RMSE = 0.78).

2.4.2.2. Removing the Oblique Response Bias

For response-contingent analysis, an oblique response bias may produce spurious serial dependence (Fritsche, 2016; Pascucci et al., 2019). To remove this effect, we applied a corrective procedure to our data as described above (results of this corrective procedure can be seen in Appendix Figure B1). In order to confirm that this was successful we ran another analysis with the aim of removing the temporal relationship between subsequent responses (alternate-flip-trial analysis). For each participant the order of even numbered trials was inverted. If a participant completed 100 trials, trial 2 was swapped with trial 98, 4 with 96, 6 with 94, and so on. This removes any correlation between responses and response errors on paired trials. As the oblique response bias is expected to apply on individual trials, we should still see serial dependence in uncorrected inverted response data but not in corrected data. This is exactly what we observe (see illustrative graph Figure 2.6), the alternate-flip-trial analysis shows several significant results pre-correction (high to high and low to low noise transitions $p < 0.05$, all data pooled across transitions $p < 0.01$,) and no such effect post-correction (all p-values in all transitions, > 0.1).

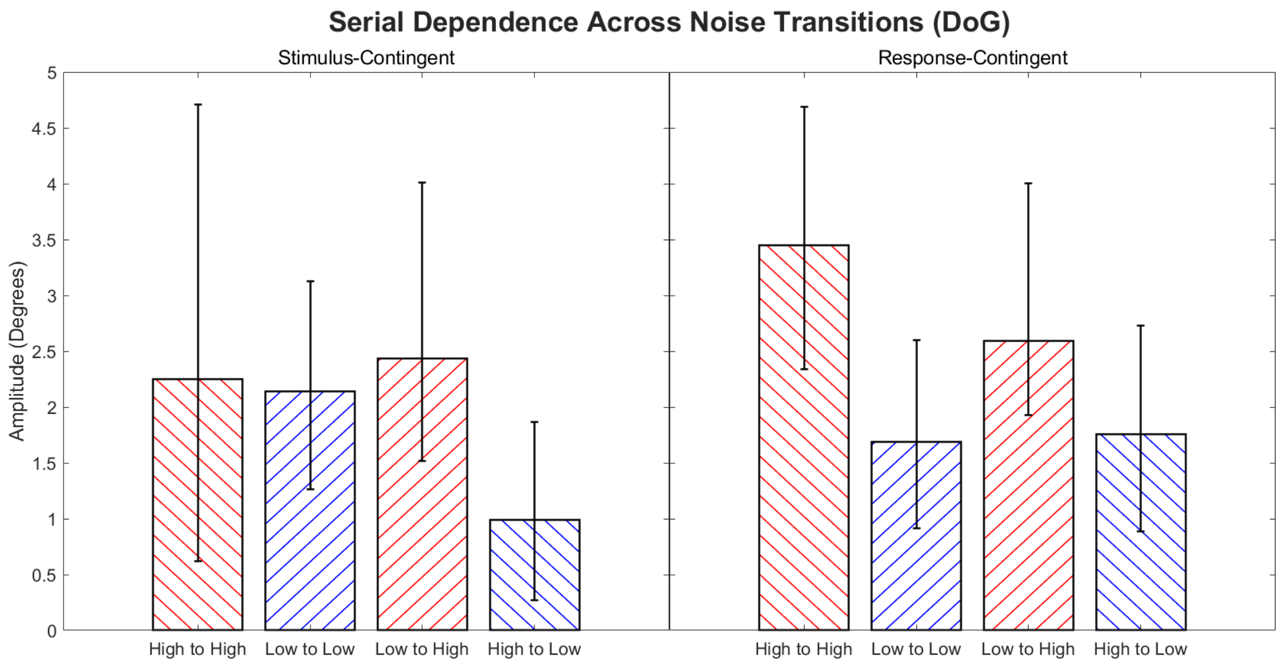

Figure 2.4. DoG Amplitudes for Each Transition. Left graphs show amplitude where difference is based on difference between current stimulus and previous response. Right graphs show data based on previous stimulus. Error bars represent 95% confidence intervals.

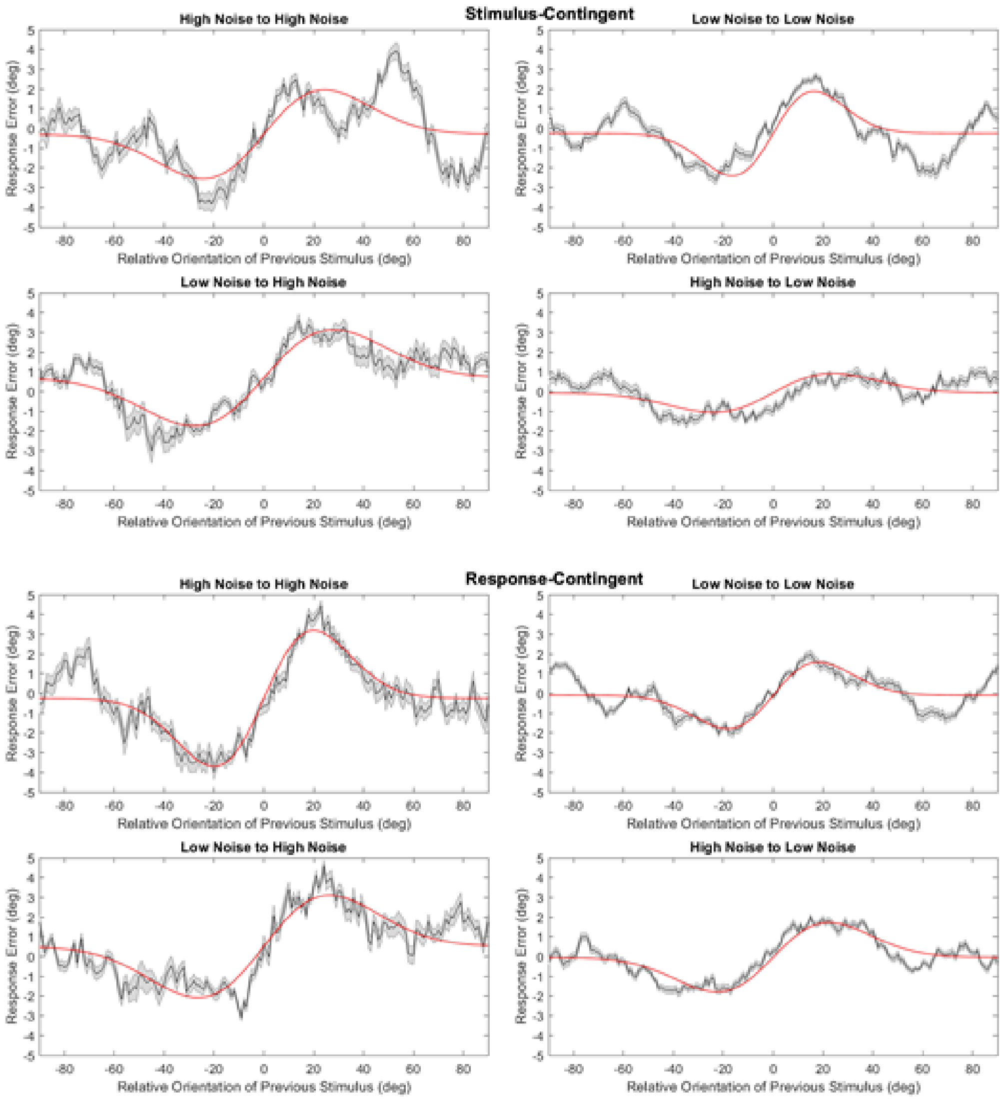

Figure 2.5. Transition conditions for pooled data. Red line – DoG fit. Black line – moving average. Grey shading indicates standard error. Top four graphs show stimulus-contingent data. Bottom four graphs show the same transitions for response-contingent data.

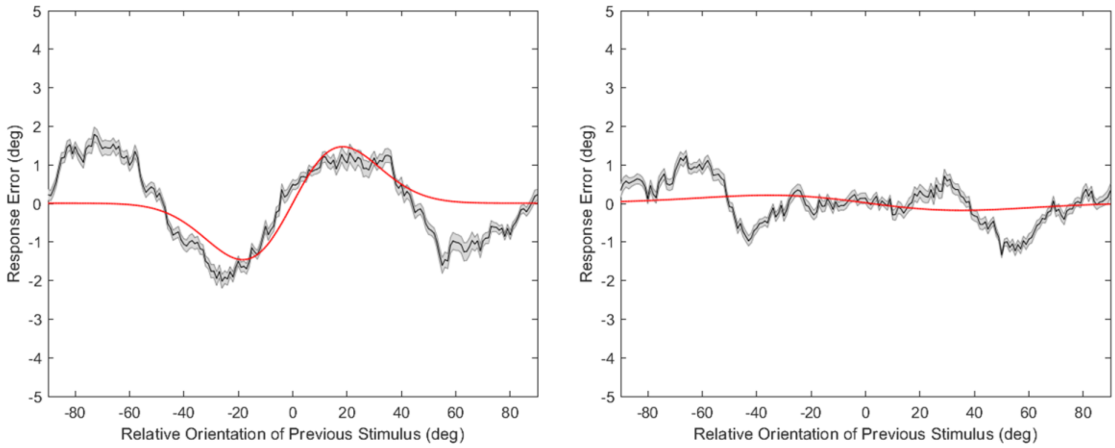

Figure 2.6. Alternate Flip Trial Data Pooled Across Transitions Before and After Correction. Left hand graph shows data subject to the flip trial analysis before correction for the oblique response bias. Right hand graph shows the same analysis with the oblique bias correction technique applied.

2.4.2.3. Comparisons between transitions

The majority of differences between transitions were revealed to be non-significant for analysis based on both previous stimulus and previous response ($p > .05$, see Table 1). For stimulus-contingent DoG analysis the difference between high to low and low to high transitions was significant ($p < 0.05$). Response-contingent analysis yielded significant differences for the transitions between high to high and low to low noise as well as high to high and high to low. Although these results are suggestive of differences between conditions, the width values associated with many iterations of model fitting were equal to the predetermined limits (0.02, 0.2). This indicates that the model fitting algorithm may have struggled to adequately fit the DoG function during the resampling procedure. This may be due to variability in portions of the response function which are not adequately described by the DoG driving variability in curve fits during the permutation procedure. The current data include clear sidebands that lie outside the central region accounted for by the DoG function (see Figure 2.5).

Table 2.1 p-values for permutation testing of difference between transition conditions. Top values in each cell are derived from analysis based on previous stimulus. Lower values are derived from analysis based on previous response.

	High to High	Low to Low	Low to High	High to Low
High to High		.92 *.04*	.87 *.18*	.30 *.03*
Low to Low	.92 *.04*		.66 *.13*	.06 *.88*
Low to High	.87 *.18*	.66 *.13*		.04 *.13*
High to Low	.30 *.03*	.06 *.88*	.04 *.13*	

2.4.3. Model-Free Analysis

As with the model-based analyses, the model free approach was carried out for orientation differences between trials based on previous stimuli and previous responses (see Figure 2.7). For stimulus-based analysis, calculation of the orientation difference from the previous trial used previous stimulus values whereas for response-based analysis the previous response was used (with the same sum of sin model residualisation as was applied for DoG analysis). For both methods the overall relationship between transition conditions was the same. A two-way repeated measure ANOVA, with factors previous stimulus and current stimulus, each with two levels (low noise and high noise), was carried out to determine the effect of noise in the current and previous stimuli on participant serial biases. This analysis suggested that the effect of noise was limited to the current stimulus ($F(1,14) = 4.68$, $p = .048$ for stimulus-based analysis, $F(1,14) = 15.04$, $p = .002$ for response-based analyses) and that noise in the previous stimulus did not contribute to the differences between conditions ($F(1,14) = .03$, $p = .864$ for stimulus-based analysis, $F(1,14) = 1.65$, $p = .220$ for response-based analysis). The interactions between current and previous noise were also not significant ($F(1,14) = .64$, p = .439 for previous stimulus, $F(1,14) = .124$, $p = .730$ for previous response).

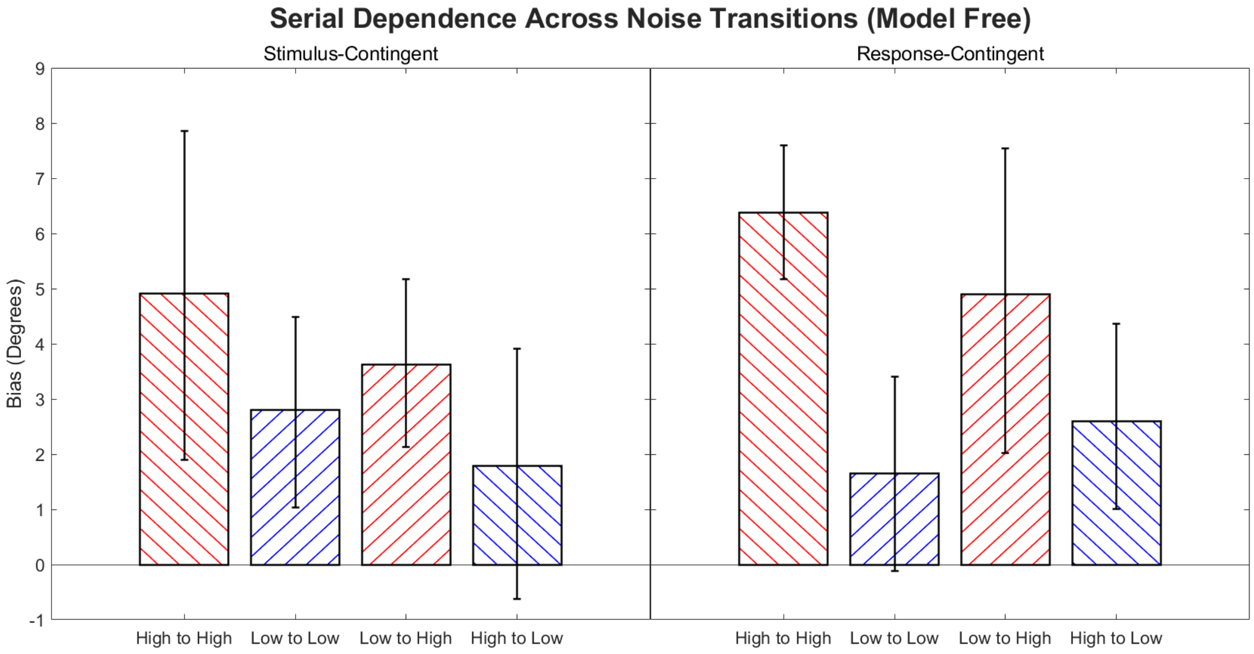

Figure 2.7. Model free biases. Left graphs show biases where difference is based on difference between current stimulus and previous response. Right graphs show data based on previous stimulus. Error bars represent 95% confidence intervals.

2.5. Discussion

We used orientation stimuli incorporating two different levels of noise to investigate the role of stimulus uncertainty in serial dependence. Participants were asked to reproduce the orientation of observed stimuli presented in succession. Participant orientation reports were consistently attracted towards the stimuli observed on the immediately previous trial. We observed that uncertainty in the presently observed stimulus can affect the scale of serial dependence. Using a model-free analysis, we found that higher uncertainty in the stimulus currently being observed can enhance the scale of this attractive effect; participant responses appeared to be more heavily biased towards previously observed stimuli when the current stimulus incorporated a higher level of noise. These findings support the idea that serial dependence is responsive to uncertainty in the current stimulus; however, we did not find similar evidence for an effect of uncertainty in prior stimulus.

Previous experiments have suggested that serial dependence may be enhanced under conditions associated with uncertainty (Ceylan et al., 2021; Cicchini et al., 2017, 2018; Manassi et al., 2018). These studies manipulated uncertainty through variation in stimulus properties known to affect the noisiness of the percept being judged (contrast, spatial frequency, cardinality), with these variations serving as a proxy for uncertainty. In the current experiment we used a direct manipulation of the uncertainty inherent in the judged percept; altering the orientation bandwidth of stimuli allowed variation in the range of orientation information presented (Beaudot & Mullen, 2006). An experiment by Fritsche (2016) used similar experimental stimuli. Their study produced results inconsistent with other experiments which document effects of uncertainty (Cicchini et al., 2018; Lidström, 2019). These latter experiments support a Bayesian narrative which suggests that serial dependence may optimally weight the reliability of stimuli (Cicchini et al., 2018).

The basic idea behind this is that for serial dependence to be useful in everyday perception, consideration of the strength of evidence for prior and current stimuli makes sense. If the current stimulus is ambiguous, it may be logical to take into account recent, more reliable perception when interpreting the current sensory evidence. Conversely, reliance on the recent past is not optimal when the evidence for current stimuli is stronger than the evidence for prior perception. In this case the better solution might involve attaching greater weight to current sensory representations rather than incorporating information from recent perception.

A number of studies have provided evidence that serial dependence may be responsive to uncertainty in a way that conforms to these Bayesian predictions. Work by van Bergen and Jehee (2019) reported a pattern of results proposed to be fully in line with Bayesian theories of perception. The authors found that greater sensory uncertainty in the prior orientation stimulus relative to the current stimulus (as decoded from fMRI) reduced serial dependence, whereas reduced relative uncertainty in the prior enhanced the effect. Similarly, the results of Cicchini et al. (2018) suggested a Bayesian pattern of serial dependence where transitions between uncertain stimuli showed greater serial dependence than transitions between relatively reliable stimuli.

The current results stand in contrast to these earlier findings. Although we observed an effect of uncertainty in the present stimulus which is consistent with these studies, the lack of evidence for an effect of uncertainty in the previous stimulus means that the Bayesian narrative is not fully supported by our results. On the other hand, the current results are consistent with the recent findings of Ceylan et al. (2021) who manipulated stimulus uncertainty through differences in spatial frequency. Lower spatial frequencies are associated with greater orientation uncertainty. The authors exploited this by using high and low frequency stimuli as proxies for low and high uncertainty respectively. The authors found that the strength of serial dependence was dependent only on uncertainty in the current stimulus, in contrast to the predictions of a Bayesian model.

Ceylan et al. propose that this inconsistency with the findings of Cicchini et al. (2018) and van Bergen and Jehee (2019) is due to the fact that all possible stimulus noise transitions were not compared in those two studies. Ceylan et al. note that the study by Cicchini et al. only looked at the transitions between low or high noise stimuli (*i.e.* low to low noise or high to high noise in the current study). In contrast, the study by van Bergen and Jehee did look at the transitions between low and high noise stimuli but did not compare these to transitions between stimuli which produced the same level of uncertainty. This leaves open the possibility that in both of these studies uncertainty in the current stimulus alone was dictating the strength of serial dependence.

A persistent issue which is often raised in studies of serial dependence concerns the underlying basis of this effect. Serial dependence could be the product of early sensory processes (J. Fischer & Whitney, 2014) or it could in fact arises from post-perceptual top-down mechanisms (Fritsche et al., 2017). Although the approach taken in the experiments of Cicchini et al. (2018) was agnostic with regards to the underlying basis of serial dependence, improvements in perceptual efficiency were taken as an indication that this process may apply at the level of underlying sensory representations. The work of Fischer and Whitney also framed serial dependence as an effect capable of producing genuine perceptual changes (J. Fischer & Whitney, 2014).

Alternatively, serial dependence may be implemented through the interaction of early visual areas with higher areas in the cortex (Vilares et al., 2012). Top-down decision effects have been suggested as a non-perceptual cause of serial dependence (Fritsche et al., 2017). Specifically, Fritsche et al. proposed that serial dependence might occur due to assimilation between current and previous decisions taking place at a post-perceptual stage as opposed to a genuine merging of perceptions. Similarly, Akaishi et al. (2014) coined the phrase "decision inertia" to describe the way that previous decisions may be repeated, a behaviour which may be based on a preference for consistency (Alós-Ferrer et al., 2016). Decision inertia could produce similar outcomes to those predicted by perceptual serial dependence. Can decision effects account for the pattern of responses found in our experiment?

Work investigating decision effects makes predictions about the impact of noise in the current stimulus. Ambiguity in the current stimulus has previously been suggested to cause a change in decision strategy (Petzold & Haubensak, 2001; Treisman & Williams, 1984). Treisman and Williams suggested that participants tend to repeat their previous response when unsure of the current stimulus. If serial dependence represents an attempt to repeat the previous decision, then we might therefore expect to see greater serial dependence when the current stimulus is ambiguous. This is exactly what we see in the current data, serial dependence is enhanced when the current stimulus is associated with greater uncertainty. This suggests that the serial effect observed could be reducible to something as simple as participants attempting to reproduce the previous stimulus when unsure on the current trial.

More complex decision-based effects have also been proposed. Pascucci et al. have suggested that a decision-weighted decoding of sensory input may instead occur (Ceylan et al., 2021; Pascucci et al., 2019). This more nuanced model involves a selective top-down weighting of the output of low-level sensory channels based on which channels have been recently informative. Responses indicating the presence of recently observed stimuli are given more weight as their continued activity can safely be assumed to indicate the continued presence of similar stimuli. This weighting is applied across channels and so can produce an attraction towards previous responses rather than strict response repetition. Crucially, in this model, the influence of the previous trial is inversely weighted by the variability associated with the current stimulus; variability in the previous stimulus having been discarded (Ceylan et al., 2021). The model therefore predicts an effect of variability in the current stimulus, but not in the previous stimulus. Ceylan et al. (2021) suggested that this post-perceptual model provides a better account of the impact of stimulus uncertainty on serial dependence than a Bayesian model. In addition, this model, while based on post-perceptual factors, does leave open the possibility of genuine perceptual change (Pascucci et al., 2019), something not necessarily predicted by response repetition.

The current experiment does not rule out either perceptual or decision-based accounts of serial dependence. However, results from Ceylan et al. (2021) suggest that, at least for orientation stimuli, serial dependence may arise from higher level sources. The authors found serial dependence between Gabor patches and orientation defined by the axis of symmetry of dot patterns (which requires higher level processing of symmetry). Serial dependence occurring beyond low-level representations suggests the possibility of post-perceptual decision effects being involved in this process.

Uncertainty-based decision effects (Treisman & Williams, 1984) are consistent with the effect of current stimulus noise observed in the current data. However, nothing in the current experiments rules out concurrent contributions of perceptual and decision effects. Although explanations invoking low-level perceptual changes (Cicchini et al., 2017; J. Fischer & Whitney, 2014) or higher level decision effects and working memory influences (Bliss et al., 2017; Fritsche et al., 2017; Pascucci et al., 2019) may appear to be in opposition, findings suggesting serial effects at different levels of the perceptual inference process could just demonstrate the utility of previous information in determining perception. More generally, if relying on recent information is useful in determining the current state of the world then we might expect this strategy to be employed in perceptual, decision and memory processes.

An issue with any manipulation of uncertainty is that it tends to come with a concurrent change in response/percept variability. As we describe previously in our analysis section, this variation indicates that the stimulus value itself might no longer accurately represent the perceived value, and this can cause the appearance of reduced serial dependence. This problem of response/percept variability in previous stimuli can be overcome using a response-contingent analysis (Fritsche, 2016). Taking the previous response as an account of observer perception eliminates this source of extraneous variation, which would otherwise act as a confound. Response/Percept variability can specifically cause the appearance of reduced serial dependence. Our main finding, of an observed increase in serial dependence for current high noise stimuli, is therefore unlikely to be driven by response/percept variability.

Notably this effect of response variation could apply to any manipulation of uncertainty, including changes in spatial frequency which have previously been used (Ceylan et al., 2021;

Cicchini et al., 2018). This may mean that any manipulation of stimuli that promotes variability carries this confound. Response-contingent analysis should ideally be applied in any experiments testing the effects of uncertainty on serial dependence.

For stimulus-contingent analysis, the misleading effects of response variability could potentially lead to the conclusion that previous stimulus uncertainty was capable of modulating serial dependence. Despite this, the current work, as well as previous stimulus-contingent studies (Ceylan et al., 2021) have failed to provide evidence of an effect of noise in the previous stimuli. However, an influence of previous uncertainty still cannot be ruled out, as it remains possible that other effects associated with noise could actually mask any impact of previous stimulus noise. Bosch et al. (2020) suggest that previous stimuli exert a concurrent repulsive effect which is strongest with greater evidence strength. This could potentially act in opposition to any noise-dependent augmentation of serial dependence, cancelling out any clear effect of previous stimulus uncertainty.

Alternatively, to account for the lack of an effect of previous stimulus uncertainty, we can appeal to Bayesian processes which incorporate stimulus volatility. In order to accurately predict the environment, previous Bayesian models of serial dependence have incorporated additional priors which model the probability of stimulus change in order to provide an account the role of uncertainty in serial dependence (Fritsche et al., 2020; van Bergen & Jehee, 2019).

In the current experiment stimulus orientation was generated randomly meaning there was no actual relationship between stimuli and any orientation similarity was coincidental. If observers can roughly quantify the probability of change in sequential stimuli, then this could also be factored into how much weight they give to prior observations. If this form of temporal uncertainty, or volatility, is high enough it might wash out any effect of previous stimulus uncertainty. Essentially, the effect of temporal uncertainty might be high enough that any contribution of previous stimulus uncertainty is negligible in comparison. This might be tested experimentally using stimuli with a perceived low or high probability of change in tandem with an associated stimulus reliability. For now, all we can say is that uncertainty in the current stimulus is capable of affecting serial dependence, regardless of whether there is an effect of previous uncertainty.

Our model-free analysis, which makes fewer assumptions about the data, revealed an effect of stimulus uncertainty which was not apparent in the DoG analysis. With regards to the latter, Figure 2.5 shows noticeable variability in response errors which is not well modelled by the DoG curve. In particular, our data exhibited response errors at large orientation differences where the DoG function predicts no such errors, an issue previously identified by Bliss et al. (2017). This means that during permutation testing these response error sidebands likely caused poor model fits to the data, hiding the significant effect revealed by model-free analysis. Although previous work has used an alternative model for data which exhibits these issues, this alternative model was also not always a good fit to data (Bliss et al., 2017). The model-free analysis may well be the best solution for data which do not conform well to the expectations of more complex models.

In conclusion, our results demonstrate that stimulus uncertainty can affect the magnitude of serial dependence; this effect appears to be limited to the effect of uncertainty in the current stimulus. Whilst it remains possible that uncertainty in the previous stimulus can affect serial dependence, evidence for this is lacking. The current research is in line with previous results which also demonstrate an effect of current stimulus uncertainty (Ceylan et al., 2021). Evidence of effects of uncertainty in prior stimuli in concert with uncertainty in current stimuli is necessary to confirm a Bayesian perspective of serial dependence.

Chapter 3. Serial Dependence is an Attraction to Prior Response

3.1. Introduction

In Chapter 2 data were analysed from both a stimulus- and response-contingent perspective. In this chapter we explore which of these approaches might be more conceptually appropriate. This will inform the analysis used in Chapter 4. This distinction between metrics of serial dependence may be relevant in addressing whether serial dependence is the result of an early perceptual mechanism or higher-level decision processes.

Fischer and Whitney proposed that serial dependence is a change in perception produced by the activity of low-level perceptual units. In the case of orientation, the activity of perceptual units selective for orientations similar to a recently observed orientation is altered. The activity of these units may be enhanced, or their selectivity altered, in a way which causes subsequent orientations to be perceived as more similar to the initially presented orientation (J. Fischer & Whitney, 2014). Results from fMRI isolating serial dependence to early perceptual areas such as V1 (John-Saaltink et al., 2016) has been argued to support the view that serial dependence can cause changes in visual perception (Cicchini et al., 2017).

The occurrence of serial dependence across such diverse stimulus types as orientation (J. Fischer & Whitney, 2014; Pascucci et al., 2019), facial identity (Liberman et al., 2014), visual variance (Suárez-Pinilla et al., 2018), body size estimation (Alexi et al., 2018), monetary value (Morimoto & Makioka, 2022) and aesthetics (Kim et al., 2019) might instead support the idea of a general process affecting perceptual decisions rather than multiple low-level perceptual effects. Experimental results have supported this idea. Ceylan et al. (2021) demonstrated serial dependence across different depictions of orientation (Gabor and dot pattern stimuli) suggesting that this showed serial dependence operating at a higher level of processing, beyond basic stimulus features. Similarly, Morimoto and Makioka (2022) showed serial dependence between numerosity of coins but also between their value, a stimulus feature which would require higher level processing of stimuli.

Multiple studies have suggested that serial dependence may be a decision-based effect (Ceylan et al., 2021; Fritsche et al., 2017; Morimoto & Makioka, 2022; Pascucci et al., 2019). The key difference in this interpretation is that rather than reflecting a perceptual blending between subsequently presented stimuli, serial dependence is instead the result of a post-perceptual attraction between decisions. Roughly put: successive stimuli do not actually look the same but nevertheless you make similar decisions about them. A major difficulty in investigating this distinction is that stimulus and decision are often very highly correlated. This can make it difficult to disentangle the contributions of stimulus and response to serial dependence.

Fritsche et al. (2017) took an approach designed to measure participant perception in a way that dissociated decisions from stimuli. In a variation of an earlier experiment by Fischer and Whitney (2014), observers were asked to compare a presented stimulus to a simultaneously displayed standard and asked if the two stimuli were the same. This approach meant that the participants decision was no longer highly correlated with the specific value of the stimulus; repeating the same decision regardless of the underlying stimulus would not produce an assimilative effect resembling the proposed perceptual blending. The authors found that previous stimuli actually exerted a repulsive effect and that any assimilation observed was likely due to carryover of previous decisions. Other work has expanded upon this idea and produced models of how decision-based serial dependence might occur (Bosch et al., 2020; Pascucci et al., 2019).

Despite the evidence for this view, there remain some experimental results which suggest that serial dependence might represent an attraction to previous stimuli rather than being a decision-based effect. On replicating the experiment of Fritsche et al. with a wider range of differences between subsequent stimuli, Cicchini et al. (2017) found that assimilative effects were evident in the equivalence task. In addition, several tasks use response methods which do not tie the participants decisions directly to the specific characteristics of stimuli. Collins (2020) demonstrated an assimilative effect in an odd one out task, where an explicit judgement on a stimulus attribute was not required. In this case, participants were not reproducing the orientation of stimuli, instead they reported the presence of an oddly oriented stimulus in an otherwise uniformly oriented array of Gabor stimuli. It was found that an observer's ability to detect the odd one out stimulus was influenced by assimilative effects from the previous trial. The orientation of a previous Gabor stimulus appeared to alter the appearance of the later odd stimulus to either make its unique orientation more, or less, detectable.

Other approaches have tried to remove prior decisions altogether. Manassi and Whitney (2022) demonstrated serial dependence with no prior decision. Observers completed only one trial of a task with a decision only being made at the end of stimulus viewing. There was therefore no prior decision which could influence their perception. Participants viewed a face stimulus which slowly aged or became younger. Ratings of the age of the final face viewed were biased in the direction of previous faces (faces which had aged were rated as younger, faces which became younger were rated as older).

Further evidence comes from Murai and Whitney (2021) using a task where Gabor stimuli were detected in a white noise image. On trials featuring only noise, with no Gabor present, participants were more likely to report the presence of a Gabor when the randomly occurring orientation information present in the white noise image corresponded to that of the previously seen Gabor. Orientation was again irrelevant to the decision made in this experiment, but the prior stimulus appeared to influence participants' perception on the current trial.

These studies leave the respective roles of previous stimuli and previous responses in serial dependence unclear. In the current chapter we attempt to differentiate between these competing influences, with implications for the nature of serial dependence. In Chapter 2 both stimulus- and response-contingent analyses were applied to data. Quantifying whether previous stimulus or previous response provides the better index of serial dependence will determine which of these analysis types is more appropriate. To test this, we used an adjustment task method which separated the expected influence of previous stimulus and previous response such that they were in direct opposition on a subset of trials. Using this method, we were able to determine which element of the previous trial produced a bias consistent with any serial bias observed in typical serial dependence trials. Previous response was found to produce an assimilative bias consistent with serial dependence. A follow up experiment tested whether this attraction to response is the result of a serial effect in decisions or an attraction to the perception of the prior stimulus.

3.2. Experiment 1

3.2.1. Materials and Methods

All experiments were approved by the Psychological Science School Research Ethics Committee at the University of Bristol.

3.2.2. Participants

17 participants took part in Experiment 1 (ages 19-37, mean = 26.05, standard deviation = 4.92, 9 female, 8 male). One participant was excluded from analysis due to poor performance (correlation between stimulus and response of less than 0.5). All participants provided

informed consent and were free to withdraw from testing at any time. Participants were entered into a prize draw for taking part in this study. All participants had normal or corrected-to-normal vision.

3.2.3. Stimuli

The stimuli used were noisy orientation patches which were randomly assigned an orientation in the range 0-179°. Stimulus generation was the same as in Chapter 2. To generate stimuli an orientation filter was applied to a 1/f noise pattern (Field, 1987). This filter consisted of two von Mises distributions mirrored around 180°. In the current experiment the concentration of the von Mises distribution was set to 4 in order to produce low noise stimuli. These stimuli were contained in a 1.5 degree standard deviation Gaussian envelope. A similar procedure was used to produce noise masks displayed between trials which consisted of a similar pattern of 1/f noise but with no orientation filter or envelope applied.

To reproduce the orientation of stimuli, participants were required to rotate the position of two white dots (width ~1° of visual angle) so that if an imaginary line were drawn between these dots it would match the orientation of the stimulus. These dots occupied opposing poles of the area previously occupied by the orientation stimulus. Adjustment dots were initially displayed at a random orientation.

A 1° fixation circle at the centre of the screen gave participants a measure of their progress through the trials. This circle was grey with a white outline. The inner grey area of the fixation circle gradually filled in black from its top pole as trials progressed.

Stimuli were presented on a 24-inch VIEWPixx 3D lite monitor (VPixx Technologies) with a resolution of 1920 × 1080 and a refresh rate of 120 Hz. All experimental scripts were created in Matlab 2019b using the Psychophysics Toolbox for MATLAB (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Stimuli were viewed from approximately 57cm in a darkened room.

3.2.4. Procedure

Participants completed 500 trials of an adjustment task with breaks permitted every 100 trials. On each trial participants saw a randomly oriented stimulus, the orientation of which they were then required to replicate.

Each trial followed the same format as Gallagher and Benton (2022). To begin the trial, an orientation stimulus was displayed for 500ms. A full screen noise mask was then displayed for 1000ms to eliminate visual after-effects. Following this, the response stimulus appeared at the same on-screen coordinates as the experimental stimulus. Immediately after the participant's response, a grey screen was displayed for 2000ms before the next trial began (trial sequence shown in Figure 3.1). Participants took roughly an hour to finish this task.

In order to isolate the effect of previous stimulus and response a subset of trials displayed stimuli with an orientation halfway between the previous stimulus and previous response. We term this subset "oppositional trials". If participant errors on a trial were between 10° and 30°, the stimulus on the following trial was placed halfway between the prior stimulus and response. This range of errors was chosen so that errors would not be so small as to reflect noise in responses and not so large as to reflect errors made due to a lack of attention to stimuli. By placing the following stimulus between the previous stimulus and response we create a situation where any biasing effect of each is in opposition.

Orientation and response stimuli were displayed at points on an invisible circle of radius 9° of visual angle which enclosed a central fixation circle (see top panel of Figure 3.1). Each orientation and response stimulus pair was presented 45° counterclockwise from the previous trial pair. Moving stimuli between spatial positions was intended to minimise retinotopic

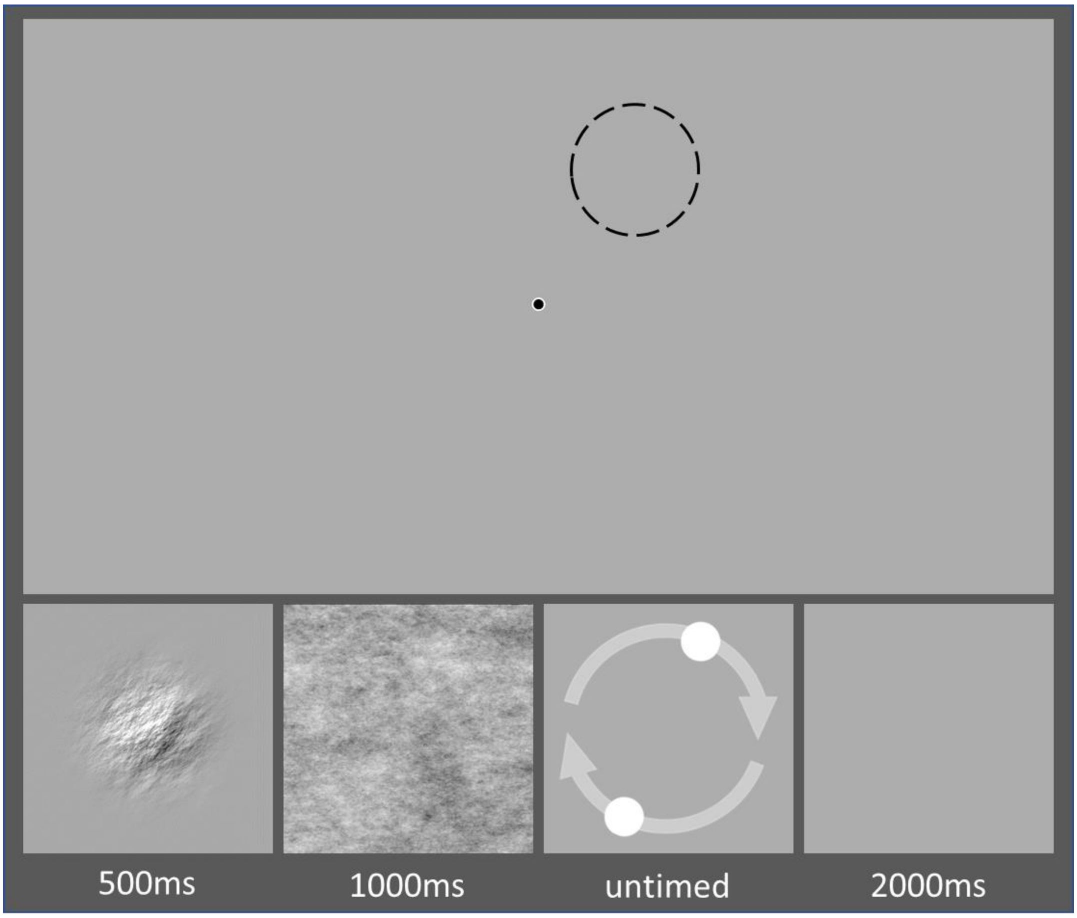

Figure 3.1. Typical trial sequence for the adjustment response portion of noise experiment. Top image shows the screen as seen by a participant, stimuli (shown below) appear in the dashed circle, fixation circle was present in all screens. Orientation stimulus appeared onscreen for 500ms. Full screen noise was then displayed for 1000ms to remove any visual aftereffects. Adjustment stimulus was then displayed in the same position previously occupied by the orientation stimulus. A blank screen was then displayed for 2000ms. The next trial sequence appeared at a point 45° counterclockwise of the previous trial sequence (dashed circle).

adaptation (Afraz & Cavanagh, 2008). Maintaining a predictable path of stimuli was intended to promote serial dependence (Liberman et al., 2016).

Responses were made using a Microsoft Sidewinder controller. Rotation of the adjustment dots used the shoulder buttons. Participants could switch between two different rotation speeds using a button on the face of the controller. Once the dots had been moved into position, a separate button was pressed to confirm and progress to the next trial. Practice trials before the main experiment allowed participants to get used to the controls and the procedure of the experiment. Data from these practice trials were discarded.

3.2.5. Analysis

Oppositional and non-oppositional trials were analysed separately. In non-oppositional trials stimulus and response are highly correlated, making it unclear which of these values best quantifies serial dependence. For any serial bias observed in non-oppositional trials, oppositional trials were used to explore whether previous stimulus or response was responsible for the bias.

Data from this experiment were analysed using a model-free method (described below). This approach was favoured over typical modelling approaches, such as the derivative of Gaussian (DoG) model (J. Fischer & Whitney, 2014), due to the nature of the data. The experimental design naturally limits the range of stimulus differences between trials, producing an insufficient data range to constrain a DoG curve, which typically covers the full range of stimulus differences from -90° to 90° (Bliss et al., 2017; J. Fischer & Whitney, 2014). In the setup of this experiment, previous stimulus and response are equidistant in orientation from current stimulus in test trials. This equal spacing from the current orientation means that the bias from each feature of the prior trial will mirror the bias from the other. The important point to take away from this bias analysis is which feature (previous stimulus or response) shows a bias of the same valence as any bias observed in non-oppositional trials.

In addition, to ensure that participant errors reflected a genuine sequential bias rather than noise, oppositional trials occurred after trials where participant error was between 10° and 30°. This means that for oppositional trials the orientation difference from the previous stimulus/response is constrained to the range 5° to 15°. To ensure a fair comparison, the same range of data from non-oppositional trials was selected for analysis. This again renders the DoG approach irrelevant as this model is typically fit to the full range of data (-90° to 90°).

Pre-processing of data was carried out according to previously established procedures (Fritsche et al., 2017; G. K. Gallagher & Benton, 2022; Pascucci et al., 2019). Rotational response biases were removed by subtracting the circular mean of response errors from raw response errors for each participant (Fritsche et al., 2017). Large errors (greater than three standard deviations from mean) were removed. Impossibly fast response times (<200 milliseconds) and large response times (greater than three standard deviations from mean) were also removed. The average percentage of trials removed by these procedures was 8.65%

In order to investigate any biases arising from prior stimulus and prior response, data were analysed using both stimulus- and response-contingent approaches (Fritsche, 2016; G. K. Gallagher & Benton, 2022). Stimulus-contingent analysis calculates the difference between successive trials based on current and previous stimuli. Response-contingent analysis instead uses the previous response as a measure of stimulus orientation on the previous trial (Fritsche, 2016). This approach has previously been used to account for variability of responses when stimuli contain noise. In this case these techniques were used to look at the serial effect arising from previous stimuli and responses.

Response-contingent analysis may produce the appearance of serial dependence due to a general oblique response bias (Fritsche, 2016). In order to correct for this bias a technique used by Pascucci et al. (2019) was applied to response contingent data as outlined in previous work (G. K. Gallagher & Benton, 2022). A sum of sin waves model was fit to the plot of participant errors against orientation (fitting performed using MATLAB 'fit' function with 'Normalize' = 'on' as per the methods of Pascucci et al.). Subtracting the predictions of this model effectively removes the influence of the oblique response bias. This procedure is hereafter referred to as "residualisation".

Although this correction would not typically be applied to stimulus-contingent analysis, due to the oppositional nature of stimulus and response, the value of one of these biases might be expected to have a corresponding effect on the opposing bias. For this reason, residualisation was also applied to stimulus-contingent analysis to avoid introducing any unintended biases (uncorrected stimulus-contingent data are shown in Appendix Figure C1).

3.2.5.1. Model-free Analysis

This model free approach involves calculating the median error over the range of stimulus differences under which serial dependence is believed to occur. The median error over the range 0° to -45° is subtracted from the median error over the range 0° to 45° to produce an overall bias value for each participant. A positive bias value indicates assimilation, a negative value repulsion (Samaha et al., 2019).

Model free biases were calculated for oppositional trials, where the stimulus was placed between the prior stimulus and response, as well as for the remaining non-oppositional data. As a form of control on the analysis procedure, a further alternate-flip-trial analysis was performed (G. K. Gallagher & Benton, 2022). This involves inverting the order of even-numbered trials. For example, in a task with 100 trials; trial 2 is exchanged with trial 98, trial

4 with trial 96, and so forth. This removes any temporal relationship between adjacent trials and so should wipe out any observed serial effect when the model-free analysis is performed on this data.

All statistical analyses were carried out in Matlab.

3.2.6. Results

3.2.6.1. Model-Free Analysis

In non-oppositional trials we observe a positive serial bias for both stimulus- and response-contingent analysis (stimulus-contingent bias = 4.03°, p = .01; response-contingent bias = 2.27°, p = .01, see Figure 3.2). We can look to oppositional trials to see which of the two factors, previous stimulus or response, causes this assimilative bias.

Response-contingent oppositional data showed a positive bias (bias = 1.23°, p = .003) while stimulus-contingent oppositional trial data showed a negative bias (bias = -1.23°, p = .02). These results suggest that the positive effect observed in non-oppositional trials is best characterised as an attraction towards the prior response.

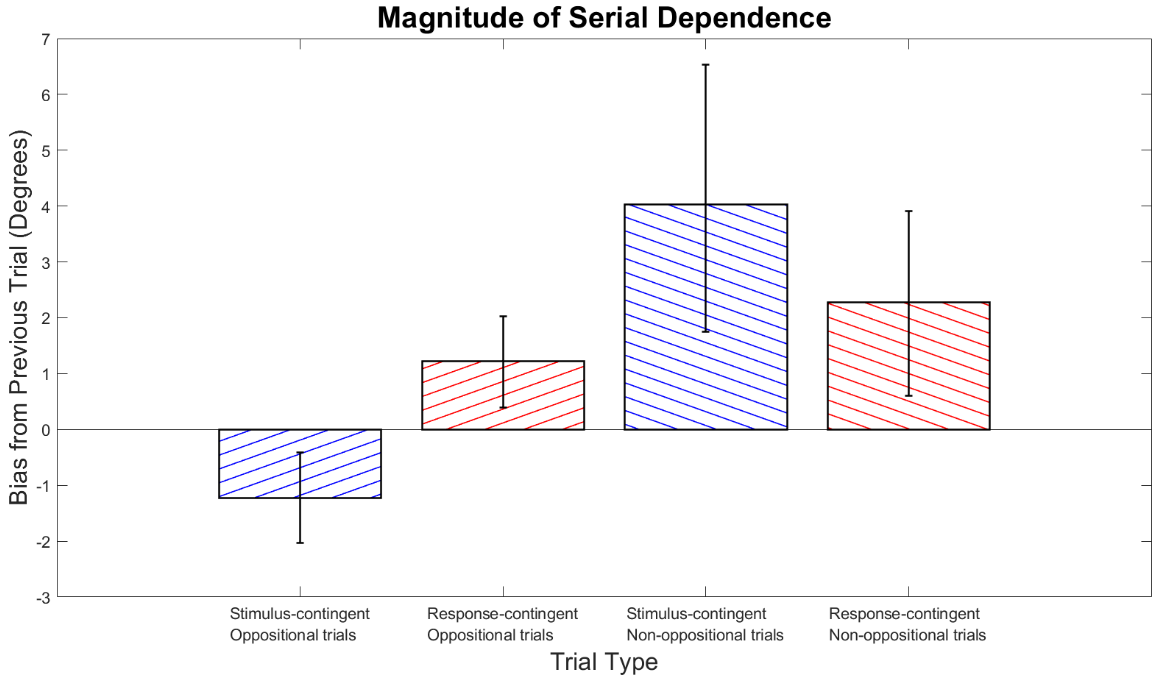

Figure 3.2. Response- and stimulus-contingent biases for oppositional and non-oppositional trials. Both forms of analysis have been subjected to residualisation for test-trials. Response-contingent non-oppositional trials were also subjected to residualisation.

3.2.6.2. Removing Oblique Response Bias

A general bias toward making oblique responses may produce spurious serial dependence in response-contingent analysis (Fritsche, 2016; Pascucci et al., 2019). To eliminate this potential confound, we applied a correction to the data as described above. To check that this correction was successful we ran an alternate-flip-trial analysis (G. K. Gallagher & Benton, 2022) which is designed to remove the temporal relationship between responses. This involves inverting the order of even numbered trials to remove any temporal order effects. If an experiment consisted of 100 trials, trial 2 would be swapped with trial 100, trial 4 with trial 98, and so on. The oblique response bias can produce spurious serial dependence regardless of any real relationship between trials. We would therefore expect to still observe "serial dependence" in uncorrected flip-trial data but not when the correction is applied.

Figure 3.3 shows the results of this analysis. Spurious serial dependence is evident in uncorrected response-contingent alternate-flip data (non-oppositional stimulus-contingent bias = 0.00°, *p* = .99; non-oppositional response-contingent bias = 4.05°, *p* = .02; oppositional stimulus-contingent bias = 0.56°, *p* = .53; oppositional response-contingent bias = 2.19°, *p* = .03). Applying residualisation removes this effect (non-oppositional stimulus-contingent bias = 0.50°, *p* = .77; non-oppositional response-contingent bias = 1.26°, *p* = .41; oppositional stimulus-contingent bias = 0.56°, *p* = .53; oppositional response-contingent bias = -1.12°, *p* = .14). As expected, these results confirm that residualisation is necessary only for response-contingent analysis.

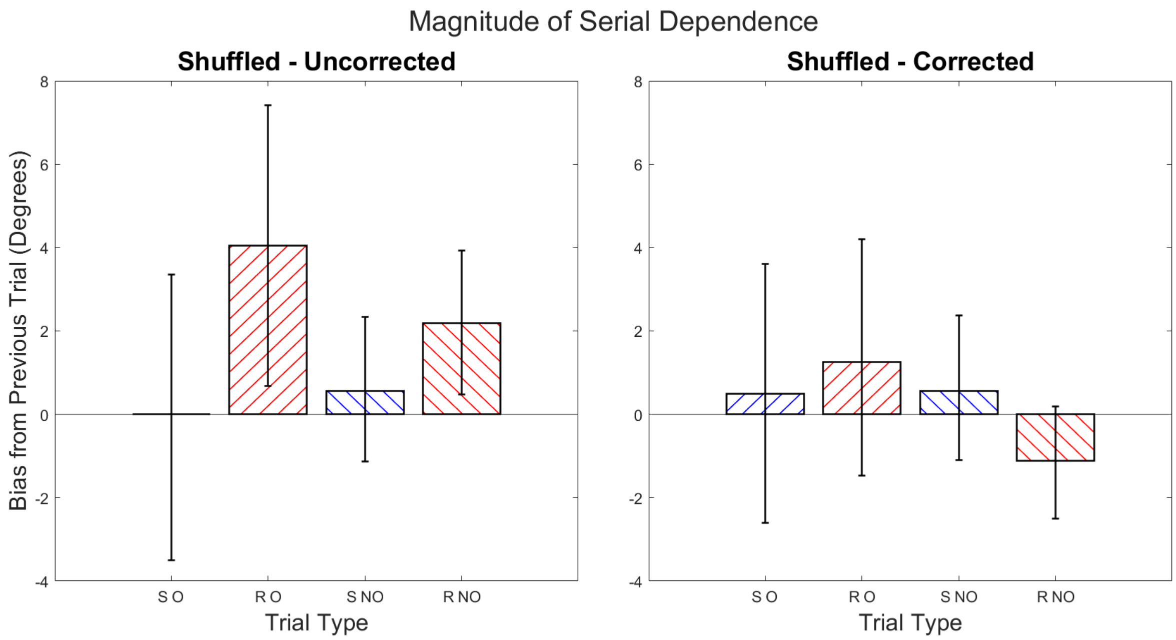

Figure 3.3. Biases in shuffled control data. Left graph shows data without oblique bias correction, right graph shows the same data with correction applied. S O - stimulus-contingent, oppositional trials, R O - response-contingent, oppositional trials, S NO - stimulus-contingent, non-oppositional trials, R NO – response-contingent, non-oppositional trials.

3.2.6.3. Response Attraction Resembles Stimulus Repulsion

Because of the opposition of stimuli on test trials, it is possible that responses which appear to be the result of attraction toward the prior response could also arise from repulsion from the prior stimulus. Both repulsion from stimulus and attraction toward response could produce a bias value with the same value due to the oppositional nature of previous stimulus and response in test trials.

However, if we consider non-oppositional trials (all other trials) we observe positive serial dependence in both response- and stimulus-contingent analyses. Stimulus and response will naturally be correlated in non-oppositional trials (mean correlation between stimulus and response = 0.84, standard deviation = 0.06). These trials demonstrate the effect of serial dependence in normal circumstances, without our oppositional manipulation. In this case we observe positive serial dependence. This attractive effect in trials where stimulus and response are highly correlated suggests that response attraction in oppositional trials is not driven by stimulus repulsion.

The negative bias apparent in stimulus-contingent analysis of oppositional trials does not imply repulsion from previous stimuli because stimulus and response were set up in direct opposition. Stimulus- and response-contingent analysis in oppositional trials is only informative about which element of the prior trial is responsible for whatever bias we see in non-oppositional trials. The other element will always be directly opposed. If the effect observed in non-oppositional trials had been repulsive then we would have concluded that stimuli elicit a negative serial effect with no implication of attraction from response.

Although the negative bias value observed for previous stimulus cannot be taken as evidence for a repulsive effect, we also cannot rule it out. If this is the case, then this repulsion must be weaker than the attractive effect observed from prior response as the overall effect when stimulus and response are correlated (non-oppositional trials) is positive.

3.3. Experiment 2

The results of experiment 1 demonstrate that serial dependence is best characterised as an attraction to the prior response. This could be interpreted as a decision-based effect where observers tend to repeat their previous decision with no change to perception. Alternatively, responses might be a better measure than objective stimulus values of what observers actually perceived on a trial. If this is true, then attraction between perceived stimuli may still account for serial dependence. To explore this possibility, we conducted a follow up experiment designed to determine whether participants perceived stimuli to be more similar to previous stimulus or previous response. This experiment incorporated a binary choice between stimuli in order to avoid decision biases and more directly assess perception (Fritsche et al., 2017).

3.3.1. Materials and Methods

3.3.1.1. Participants

17 new participants took part in Experiment 2 (ages 19-37, mean = 26.47, standard deviation = 5.28, 11 female, 6 male). All participants provided informed consent and were free to withdraw from testing at any time. Participants were entered into a prize draw or received course credit for taking part in this study. All participants had normal or corrected-to-normal vision.

3.3.1.2. Procedure

In this experiment, after making an initial adjustment task decision on a high noise stimulus, participants then completed a perceptual comparison task on a subset of trials defined in the same way as in Experiment 1 (adjustment errors greater than 10° but less than 30°). This task was designed to assess whether an observer’s response on the current trial was attracted toward prior stimulus or response orientations when the current stimulus orientation was placed between these two values.

Because adjustment and comparison tasks were paired, stimulus noise levels could be optimised for different tasks. Noise on the initial adjustment task was higher (von Mises concentration of 1) in order to encourage differences between stimulus and response large enough to increase the proportion of oppositional trials. During the subsequent comparison task noise was reduced (von Mises concentration of 4) to reduce the difficulty of this task and produce a more accurate response.

On oppositional trials the stimulus orientation presented following the initial adjustment task was again placed in between the previous stimulus value and the response value, However, instead of completing another adjustment task, participants now completed a comparison task. Three stimuli were displayed. One test stimulus featuring the midpoint orientation was displayed in the same position as the prior adjustment stimulus. Two additional stimuli were displayed 10.5° of visual angle above and below the position of the midpoint orientation stimulus (see Figure 3.4.). These two additional stimuli displayed new orientation values which were calculated as follows; the stimulus orientation and the response orientation from the previous trial were rotated 10° away from each other to enhance the difference between them. So, for an initial 45° stimulus with an associated response of 60°, rotation of these values produced 35° and 70° orientation values for stimuli to be displayed on the comparison task (see left column of Figure 3.5. for an example). Participants were asked to decide which of these two comparison stimuli best resembled the orientation of the mid-point orientation stimulus.

In this task we assume that response is a better index of observer perception that the stimulus itself (Fritsche, 2016). So, if serial dependence is an attraction to previous percept, then perception of the mid-point stimulus presented on oppositional trials should be attracted towards the previous response. This should cause participants to pick the stimulus displaying an orientation closest to the previous response value. However, if serial dependence is an attraction between subsequent decisions, then we might expect serial dependence to be absent during the binary choice task; the decision being made is now different (comparison rather than adjustment) so the previous decision cannot be repeated in the current trial. This should result in no clear preference for either stimulus or response values.

On non-oppositional trials (i.e. those where the previous adjustment error did not meet criteria) three stimuli were again displayed. However, in this case the top and bottom stimuli were randomly assigned the same orientations as the previous stimulus and response. The orientation of the middle stimulus was set to the orientation of either the previous stimulus or response orientation rotated 10° away from the previous response or stimulus orientation respectively. So, if the orientation of the previous stimulus was 90° and the response was 95°, the orientation of the middle stimulus could be 80° or 105°. The higher and lower stimuli would be assigned the orientations of the prior stimulus and response (90° and 95°). Assignment of these orientations to higher or lower positions was random (see right column of Figure 3.5. for an example). This display of orientations was selected to provide participants a clear answer on non-oppositional trials.

In this task the adjustment stimulus and response display for the adjustment portion of the experiment took place at a fixed point either 9° to the left or right of the fixation circle (randomly assigned in first block then alternated in each subsequent block). This position was maintained within a block of trials, similar to previous studies (J. Fischer & Whitney, 2014; Pascucci et al., 2019). This stimulus display position was chosen to allow the two comparison stimuli to be displayed above and below the test stimulus, in positions which did not overlap with any stimulus previously displayed in the adjustment task (see Figure 3.4. for example stimulus positions in the comparison task). Participants completed five blocks of this task. Each block consisted of 100 paired adjustment and comparison tasks. This experiment took participants around an hour and fifteen minutes to complete.

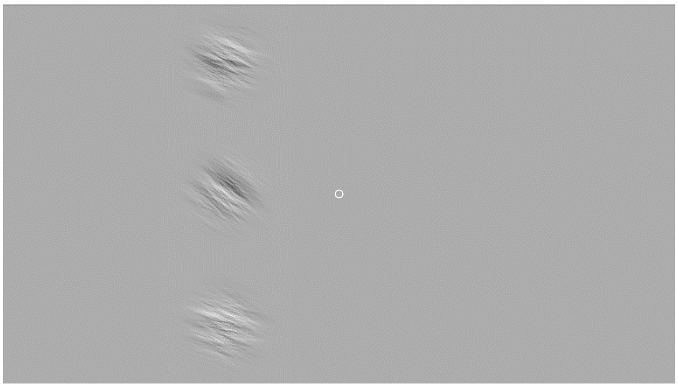

Figure 3.4. Typical choice screen seen by participants in experiment 2. This screen was displayed after an initial adjustment task response as performed in experiment 1.

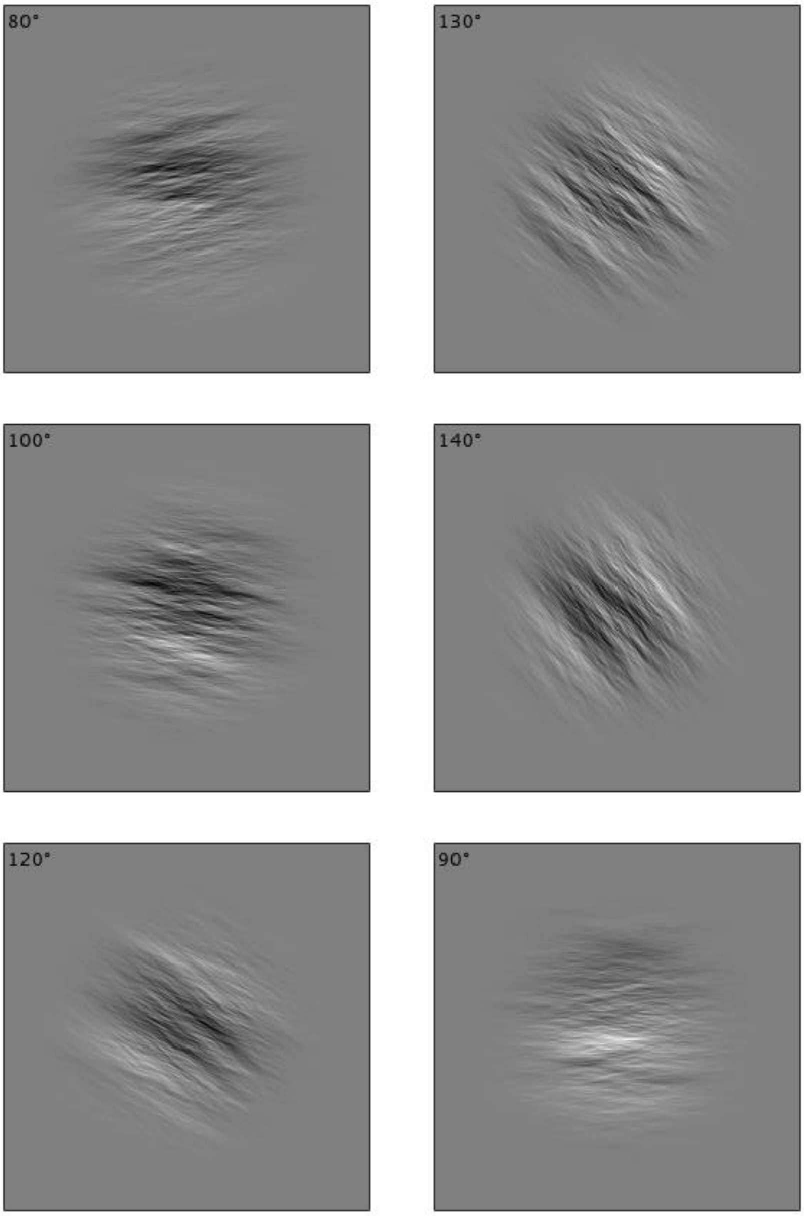

Figure 3.5. Stimuli in the binary choice task. Left column shows stimuli on an oppositional trial where the participant saw a 90° stimulus on the prior trial and provided a response of 110°. Previous stimulus -10° is displayed above, previous response +10° is displayed below, middle stimulus orientation is midway between prior stimulus and response. Right column shows stimuli displayed on a non-oppositional trial where the participant saw a 90° stimulus on the prior trial and provided a response of 130°. Previous response is displayed above, previous stimulus is displayed below, middle stimulus orientation is previous response orientation +10°. The correct answer in this case would be the top (previous response orientation) stimulus.

3.3.2. Analysis

Data for experiment 2 were analysed by comparing the ratio of participant responses (previous response direction vs. previous stimulus) on oppositional trials. The mean ratio was compared to the expected ratio of 0.5 (which assumes no preference for either option) using a one-tailed t-test.

3.3.3. Results

In the standard comparison participant responses suggested that midpoint stimuli were perceived as being more similar to the previous response (mean proportion of response-like answers across participants = 0.56, 95% confidence interval [0.52, 0.60] standard deviation = 0.07, one sample $t(14) = 3.53$, $p = .003$). Non-oppositional trials featured an objectively correct answer, central stimuli were generated with an orientation closer to either previous response or previous stimulus. Participant responses on non-oppositional trials were generally correct (accuracy calculated for each participant and then averaged = 66.13%, 95% confidence interval [60.98, 71.29] standard deviation = 9.3%, one sample t-test against 50%, $t(6.71)$, $p < 0.001$) suggesting that participants were able to complete the task successfully.

3.4. Discussion

Using a task which experimentally separated the influence of previous stimuli and previous decisions, we observed an attraction to previous decisions in orientation stimuli. In a follow-up experiment we found that participants report stimuli bearing a greater resemblance to previous adjustment responses than previous stimuli. Crucially, the task in this experiment involved a different form of decision, a perceptual comparison. Attraction to responses could be a result of a decision-based serial effect, such as a tendency to repeat the same choice. Alternatively, responses might be a better representation of perception than objective stimulus values. Attraction to previous responses in the perceptual comparison task might suggest that the latter hypothesis is true: observer evaluations of stimuli are attracted toward their perception of previous stimuli.

The underlying basis of serial dependence remains a topic of debate in the literature. One proposal is that this effect arises from early sensory processes (J. Fischer & Whitney, 2014). The visual system might blend current input together with previous information to produce a genuine change in perception. Alternatively, serial dependence may be a product of post-perceptual top-down mechanisms (Fritsche et al., 2017). In this case serial dependence might occur due to assimilation between current and previous decisions as opposed to a blending of perceptions. This explanation would fit with existing theoretical frameworks which describe serial decision biases, such as a tendency to repeat previous decisions termed "decision inertia" (Akaishi et al., 2014). Our experiments were designed to differentiate between perceptual and decision accounts of serial dependence.

In experiment 1, non-oppositional trials featuring random stimulus orientations yielded a positive bias typical of serial dependence using both stimulus- and response-contingent analyses. However, in trials where the influence of previous stimulus and response are in opposition, we observe a positive bias towards the previous response. The overall positive bias observed in non-oppositional trials likely reflects the strong correlation between stimulus and response under normal circumstances (Morimoto & Makioka, 2022). While the previous response may still be driving the observed serial dependence bias in these trials, the close relationship between stimulus and response creates the impression that previous stimuli can drive assimilative biases.

Potential attraction to stimuli might seem implausible, given that we only have access to perceptual representations of stimuli rather than their objective value. Decisions could be taken as a more accurate reflection of observer perception of stimuli and so might be expected to better quantify the source of any attraction to prior percept. However, previous research has focussed on stimuli as the source of serial dependence (Cicchini et al., 2017; J. Fischer & Whitney, 2014). In this case stimuli might serve as a proxy for changes in orientation channel tuning induced by sensory encoding, which occurs as a result of stimulus exposure prior to awareness or decisions (Moon & Kwon, 2022). Studies that do report attractive effects of decisions often report repulsive effects of stimuli at this low level of stimulus encoding (Moon & Kwon, 2022; Sadil et al., 2021; Sheehan & Serences, 2022).

One valid criticism of the current studies might be that an apparent attraction towards the previous response could be an attraction to the final orientation of the previous response stimulus (i.e. the circles which appear when participants begin making their response). However, any orientation information expressed by these stimuli was not directly displayed, instead being expressed in the relative position of the dots, similar to adjustment stimuli used in previous studies (Ceylan et al., 2021; Cicchini et al., 2017). In addition, previous research has shown serial dependence between stimuli, as opposed to response stimuli, when no response bar was presented (Manassi et al., 2017) or when participants were required to produce mirrored orientation responses as opposed to directly reproducing stimulus orientations (Cicchini et al., 2017).

The experiment of Cicchini et al. also implies an important consideration about the nature of serial dependence. In the case of mirrored responses, stimuli would presumably be more highly correlated with perception than mirrored responses. This suggests that attraction toward responses observed in standard experiments without mirrored responses, such as experiment 1, represents an attraction to prior percepts rather than to prior decisions.

Attraction to responses might reflect an assimilative effect between previous and current decisions or it could reflect the fact that there is sometimes a disparity between reality and perception. It is worth noting that the study which first used the response-contingent approach implemented in analysis of experiment 1 noted that response is more likely than objective stimulus values to resemble subjective perception (Fritsche, 2016). This may be particularly true in the case of experiment 2 where initial higher noise on a stimulus could induce a greater difference between objective stimulus values and perception. Responses may therefore be more likely to reflect observer perception than objective stimulus values in this case.

The results of experiment 2 might be taken to suggest that attraction towards the previous response does represent the relationship between response and perception. Participants reported mid-way stimulus orientations as looking more like previous response orientations than previous stimulus orientations. This may reflect an attraction to the previous perception of stimuli. Perception is not always accurate, and responses may in this case be a better index of participant perception than objective stimulus orientations. By this logic, attraction to responses in experiment 1 could arise from an attraction between percepts of stimuli rather than between decisions.

However, the results of experiment 2 could also arise from stimulus repulsion if it is assumed that assimilative effects were not present. For example, if serial dependence is purely an attraction between decisions, then switching from the adjustment task to the comparison task could negate the attractive sequential effect (Fritsche et al., 2017; Suárez-Pinilla et al., 2018). The opposition of stimulus and response influences means that we might still observe what looks like an attraction towards the previous response orientation only because of a repulsive effect from the previous stimulus orientation, which could be due to stimulus adaptation.

However, previous experiments have observed serial dependence with consistent stimulus positions across trials, despite the potential for adaptation (J. Fischer & Whitney, 2014;

Pascucci et al., 2019). In addition, on non-oppositional trials, any repulsive effect was not strong enough to prevent participants from selecting the response option nearest the previous stimulus most of the time (66.13% correct). Nevertheless, it remains possible that some repulsive effect might exist. However, results from other studies demonstrate attraction between stimuli after decisions which are orthogonal to judgements of stimulus characteristics (Collins, 2020; Murai & Whitney, 2021). This suggests that attractive effects may persist even across tasks featuring different decisions.

Experiment 2 could be repeated with alterations in procedure to minimise any repulsive effects arising from stimulus adaptation. One way of doing this might be to change the position of successive stimuli in a similar way to experiment 1. By rotating stimuli around the screen any retinotopic adaptation might be avoided. The issue this presents is that the screen coordinates of additional stimuli displayed during the comparison portion of this experiment might overlap with the coordinates of previously displayed stimuli. To avoid this, comparison stimuli could be presented either side of the test stimulus, along the radial axis drawn from the fixation circle to the point of adjustment stimulus presentation, rather than towards the top and bottom of the screen. The problem with this approach is that this creates a difference in the position of comparison stimuli relative to the periphery of vision. These eccentricity differences might create differences in the uncertainty associated with each stimulus, which could affect serial dependence (Manassi et al., 2019). As established in Chapter 2, uncertainty in the current trial can affect the extent of serial dependence. Randomly assigning stimulus- and response-adjacent comparison stimuli to the near or far positions might help wash out any effect of periphery-related uncertainty. However, some results suggest that eccentricity does not affect serial dependence (Suárez-Pinilla et al., 2018). This might be confirmed with a control analysis to check if observers expressed a preference for near or far positions.

It might also be worthwhile repeating the above experiments with the same participants completing both tasks. This would allow quantification of each participants repulsive biases using existing analysis techniques (Moon & Kwon, 2022; Sadil et al., 2021; Sheehan & Serences, 2023). Sadil et al. (2021) demonstrated that it was possible to separate attractive and repulsive effects in each response. If repulsive effects in non-oppositional trials were found to be too small to account for the appearance of a response decision in experiment 2 by way of stimulus repulsion, this would suggest that a participant chose the response option because it bore a greater resemblance to their perception of the central stimulus.

While it remains unclear whether attraction to responses does reflect attraction to prior perception, previous studies have suggested that serial dependence is better characterised as an attraction to the previous percept (veridical or not) as opposed to attraction between the current percept and previous low-level encoding of stimuli. St. John-Saaltink et al. (2016) found that serial dependence was dependent on the perception of the previous stimulus (accurate or not). Other studies have used techniques which attempt to influence the content of conscious awareness. Fornaciai and Park (2019a) used backwards masking to demonstrate that awareness of a stimulus was necessary to induce serial dependence. Similarly, Kim et al. (2020) report serial dependence arising from consciously perceived stimuli in a paradigm which used binocular rivalry to induce switching between perceptions.

In conclusion, our results add to a growing body of evidence that suggest serial dependence is best quantified as an attraction to previous responses. The results of experiment 2 could be taken to suggest that this represents an attraction towards perceptions of prior stimuli. However, this is not entirely clear due to limitations of this experiment which prevent unambiguous interpretation.

Chapter 4. Prior Confidence Predicts Serial Dependence in Orientation Judgements

4.1. Introduction

Chapter 2 explored the impact of uncertainty on serial dependence by manipulating stimulus noise. This demonstrated that current stimulus uncertainty can affect serial dependence. However, Chapter 3 established that prior response is a better measure to quantify serial dependence. As well as objective stimulus uncertainty, it might make sense to take into account some measure of the quality of previous responses. If the previous decision was incorrect then it shouldn't be used to inform current choices. However, observers often do not have access to information about the quality of their previous responses. Instead, they must rely on proxy measures such as their own internal evaluation of their decisions. Subjective confidence might be an appropriate proxy measure of uncertainty to consider.

Several studies do report correlations between confidence and serial effects. Suárez-Pinilla et al. (2018) report serial dependence only following high confidence decisions on previous stimuli. Similarly, Samaha et al. found that high confidence in the prior decision can enhance serial dependence (Samaha et al., 2019). Bosch et al. (2020) found that both high explicit confidence ratings and fast responses, a common proxy for high confidence (Braun et al., 2018), lead to enhanced serial effects on the following trial. In addition, the closely related effect of confirmation bias has also been suggested to be enhanced by prior high confidence (Rollwage et al., 2020) and more general repetition biases can also be modulated by previous confidence (Braun et al., 2018),

While everyone has an intuition of what confidence is, it is harder to pin down a scientific definition of this concept. Confidence might be considered a measure of the quality of a representation of a stimulus (Yeung & Summerfield, 2012). However, Pouget et al. (2016)

suggest that confidence may be defined in terms of choices, representing the probability that a choice is correct. This choice may be a decision (A or B) or proposition (A is red) and can be overt or covert. The authors make the point that this quantity is distinct from objective uncertainty, which represents a more general choice-independent measure which may be used to compute confidence after a choice is made.

Crucially, observers cannot directly assess the accuracy of their choices prior to feedback. However, there are numerous ways that the perceived probability of a correct decision may be constructed. The brain might approximate this probability by considering the balance of evidence for a choice and its alternatives at the time a choice is made (Fetsch et al., 2014). Alternatively, confidence could be constructed from further post-decisional processing of the same information used to make a choice (Balsdon et al., 2020; Hilgenstock et al., 2014; Pleskac & Busemeyer, 2010)

Multiple signals might also be incorporated into a confidence judgement, perhaps as many as are available in any given task (Rausch et al., 2018). Elements of stimuli such as visibility and variance of the dimension of interest might be used to inform an observer's sense of the probability of being correct (Rausch et al., 2018). Whatever the timing and elements involved in its construction, confidence may act as a subjective measure of the quality of a perceptual representation and the perceived validity of any decision made using that representation.

Given that confidence may provide a measure of likelihood or reliability for the previous choice, this is an obvious measure to use when considering how much weight to give to prior experience. High confidence in a prior decision might cause you to give it more weight; high confidence probably indicates that the choice was accurate and therefore maybe still informative about the current state of the world. On the other hand, if a previous choice was made with low confidence, it is likely to be inaccurate and should not be incorporated into your interpretation of the environment now. A lack of confidence in current choices might also be relevant. Low confidence in the current choice could indicate that you should rely more on previous information. Alternatively, higher confidence in the current choice suggests that previous decisions can be disregarded. Confidence could therefore act to influence the strength of serial dependence by influencing the weight given to past and current stimuli. This weighting of prior and current evidence by perceived uncertainty (confidence) to produce optimal inferences resembles a Bayesian perceptual strategy, something which has previously been proposed as a basis for serial dependence (Cicchini et al., 2018; van Bergen & Jehee, 2019).

The possible role for confidence in serial dependence has been taken as evidence that this effect is regulated by top-down mechanisms (Fritsche et al., 2020). The specific nature of serial dependence might affect how much we expect confidence and feedback to influence this process. If serial dependence is a low-level process (J. Fischer & Whitney, 2014), occurring in sensory brain regions without any influence from "higher" areas then we might expect confidence (generally regarded as a higher-level metacognitive process, (Yeung & Summerfield, 2012) to be inconsequential to this process. Alternatively, if serial dependence occurs because higher level brain areas influence earlier processing regions (Pascucci et al., 2019) then higher-level confidence judgements and recognition of errors might change the extent of serial dependence.

To confirm any link between confidence and serial dependence it may be useful to experimentally manipulate confidence. One way to influence observer confidence is to provide feedback following a choice (Skewes et al., 2021). Negative feedback would be expected to reduce confidence in a decision and hence decrease any effect of prior confidence on serial dependence. High confidence responses will generally be associated with low error and positive feedback. In order to explore the link between serial dependence and confidence, we applied false feedback in a subset of trials in an orientation judgement task. Confidence can be an indicator of performance (Ais et al., 2016; Samaha & Postle, 2017); false feedback serves to dissociate confidence from performance by reducing confidence. In this case false feedback signalled reduced accuracy; the scale of participant errors was exaggerated. If feedback reduces prior confidence, then providing increased error feedback when observer confidence is high should have more of an effect than when observer confidence is low to begin with. This reduction in confidence should reduce the weight attached to prior decisions, making serial dependence a non-optimal outcome.

4.2. Materials and Methods

This study was approved by the Psychological Science School Research Ethics Committee at the University of Bristol.

4.2.1. Participants

41 participants took part in this experiment (ages 18-30, mean = 19.95, standard deviation = 2.23, 30 female, 11 male). All participants provided informed consent and were free to withdraw from testing at any time. Participants were given course credit for taking part in this study. All participants had normal or corrected-to-normal vision.

4.2.2. Stimuli

Orientation stimuli were generated by applying an orientation filter to a pattern of 1/f noise (Field, 1987) following the procedure of stimulus generation used in Chapter 2. The noise level of stimuli was controlled by the concentration of the von Mises distribution. Stimuli were orientation patches containing a fixed level of noise (see Figure 4.1 bottom left panel). The noise level of these stimuli was selected based on experience with a previous experiment using low and high levels of noise (G. K. Gallagher & Benton, 2022). A noise level which was more difficult than the low noise condition of that previous experiment was used (concentration parameter of von Mises = 1). This was to induce a sense of ambiguity about stimuli so that participants would be more open to accept false feedback.

Adjustment stimuli appeared at the same area previously occupied by orientation stimuli. Response stimuli consisted of white circles (width ~1° visual angle). Before making a response, an initial white circle appeared at the centre of the area previously occupied by a stimulus, indicating response requirement. Two more circles appeared onscreen during participant response. The third panel from the left in the bottom row of Figure 4.1 shows an example adjustment stimulus.

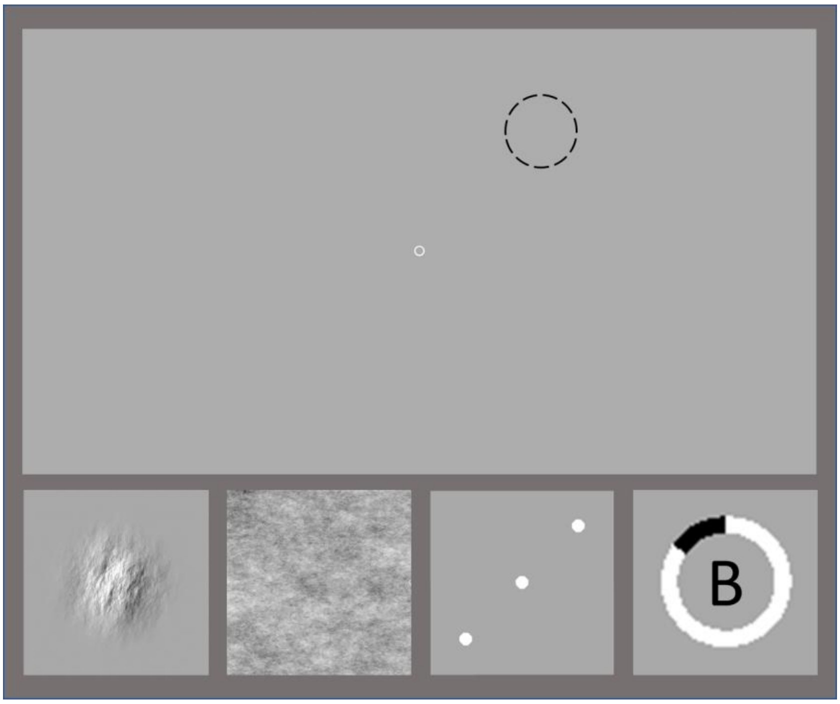

Figure 4.1. Typical trial sequence for feedback task shown from left to right in bottom panels. Participants saw a noisy orientation grating for 500ms followed by full screen noise for 1000ms. Participants were then required to reproduce the orientation observed by adjusting the position of adjustment dots. Angle of the dots expressed orientation. The distance of the outer dots from the central dot indicated confidence. After making a decision, participants were given feedback for 2000ms. Trial-by-trial feedback was given in the form of a black curve following the circumference of the fixation circle. The length of this curve indicated the

scale of error. The direction of this curve from the 12 o'clock position indicated whether error was clockwise or anticlockwise. Participants also received a grade indicating their overall performance on a scale from A-F. Feedback was presented in the central fixation circle (width 1° visual angle). Experimental and adjustment stimuli were displayed at points 9° of visual angle away from the fixation circle. Dashed circle in top image shows typical stimulus position. This position was rotated by 45° counter-clockwise relative to the fixation circle on each trial.

4.2.3. Procedure

Participants completed 500 trials of an adjustment task with breaks permitted every 100 trials. On each trial participants saw a stimulus with a random orientation which they were then required to reproduce.

A grey fixation circle (width 1° visual angle) with a white border was presented in the middle of the screen. As trials progressed the uppermost row of grey pixels within the circle was replaced with black pixels until the entire fixation circle was black. This gave participants a measure of their progress through the trials.

Each trial followed the same format as Gallagher and Benton (G. K. Gallagher & Benton, 2022). First an experimental stimulus was presented for 500ms. This was followed by full screen 1/f noise for 1000ms to eliminate after-images. A response stimulus (described above) then appeared at the same location which allowed participants to provide simultaneous orientation and confidence judgements.

Participants reproduced the orientation observed using the left analog stick of a Sony DualShock 4 controller. Participants were able to move this joystick in the direction of the displayed orientation. The analog stick allows for a full 360° range of motion. As soon as the analog stick was moved, two additional white circles appeared at opposing points on the circumference of the adjustment stimulus area, oriented to match the participants response

(See Figure 4.1). This adjustment stimulus has a rotational symmetry order of 2; angles 180° apart look the same. Hence, a joystick orientation of 90° and 270° appear identical onscreen. This allowed the 360° range of the analog stick to represent values in the range from 0° to 180°.

Participants could further adjust the position of these dots with the analog stick before confirming their choice with the X button. The distance of the two outermost adjustment dots from the central dot was also under participant control. Moving the analog stick further from its central starting position also moved the exterior dots further out from the centre. Participants were instructed to vary this distance to indicate their confidence in their adjustment orientation. Moving the circles further out from the centre indicated higher confidence.

Confidence and orientation judgements were incorporated into the same response in order to minimise any delay between them, as well as minimising the potential problems of alternating between tasks. In short, when participant switch between tasks they may not maintain the criteria they use to make judgements on one task type across tasks (Chang et al., 2017).

After their response, participants were given immediate feedback indicating the degree of their error on an otherwise uniformly grey screen for 2000ms. This feedback was given in the form of a curved black bar extending clockwise or counter-clockwise (dependent on the direction of error) from the top of the fixation circle (see Figure 4.2). The length of this bar varied based on the scale of participant error. This feedback was intended to provide information about the scale of errors without directly displaying the correct answer to participants.

On 50% of trials participant error was exaggerated by a random value ranging from 30° to 50°. This was intended to manipulate participant confidence. Continuous feedback rather than a binary right or wrong feedback message was intended to induce changes in confidence without causing participants to entirely disregard their previous judgement. In addition, coding responses as right or wrong would demand a subjective choice on the part of the experimenter over what constitutes an incorrect response in this adjustment task where participants are unlikely to produce precisely the correct answer.

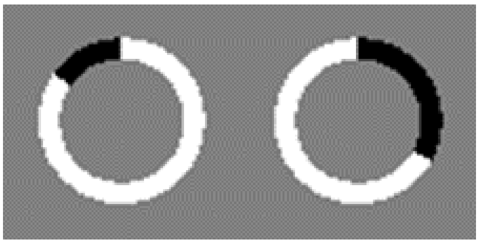

Figure 4.2. Examples of feedback given to participants. The left image depicts a small anticlockwise error. The right image shows a large clockwise error.

Participants were also provided with a “grade” ranging from A to F which appeared in the centre of the fixation circle. Participant were told that this grade reflected their performance over completed trials subject to some form of weighting. This grade was intended to maintain participant engagement despite unreliable feedback on individual trials. While a participant might be inclined to disregard a previous trial or alter their responses based on unreliable feedback, the grade provided a measure of overall performance. This allowed participants to judge their own understanding of the task and was designed to avoid disengagement due to false feedback.

The grade provided actually only reflected performance on the previous ten trials. One point was awarded for each response made by the participant which was within 10° of the stimulus. The number of points awarded over the previous ten trials determined the grade. Reporting an actual account of overall performance would result in a diminishing influence of errors as trials continued, allowing participants to disregard later errors ("I keep getting large/small errors but my grade hasn't changed so who cares"). Limiting the grade to the previous ten trials allows it to be more dynamic, making trial by trial feedback more believable.

Participants completed a practice task using Gabor stimuli until they were comfortable with the control scheme and requirements of the task. Another practice task using the stimuli shown in the experiment, but no feedback was also completed to familiarise participants with stimuli. Data from these practice tasks were not included in analysis. This experiment took participants around an hour to complete.

The position of each orientation and stimulus pair was rotated around the central fixation circle by 45° counter-clockwise from trial to trial. The consistent orbit of stimuli was designed to promote serial dependence as consistent object paths may promote serial dependence (Liberman et al., 2016). Stimulus display movement was also intended to minimise retinotopic adaptation (Afraz & Cavanagh, 2008).

Stimuli were presented on a 24-inch VIEWPixx 3D lite monitor (VPixx Technologies) with a resolution of 1920 × 1080 and a refresh rate of 120 Hz. Viewing distance was approximately 57cm. All experimental scripts were created in Matlab 2019b using the Psychophysics Toolbox (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). Stimuli were viewed from approximately 57cm in a darkened room.

4.2.4. Analysis

Data from this task were analysed with a common model-based approach (J. Fischer & Whitney, 2014) as well as a model-free method (Samaha et al., 2019).

Pre-processing methods were used to remove sources of response bias not related to serial dependence, using established methods (Fritsche et al., 2017; Pascucci et al., 2019). Any tendency to report a particular direction was moved by subtracting the circular mean of each participants response biases from raw error data (Fritsche et al., 2017).

Errors greater than three standard deviations from the mean error of each participant were removed (Fritsche et al., 2017). This procedure resulted in an average of 1.25% of trials being removed for each participant in experiment. Response times greater than three standard deviations from the mean were also removed (Pascucci et al., 2019). This procedure resulted in an average of 1.49% of trials being removed for each participant.

Participants with very high overall error (< 0.5 correlation between stimulus and response) were removed (3 participants). In order to ensure that participants were providing simultaneous confidence judgements, participants that did not use at least 10% of the available range of confidence judgements were removed (6 participants). In addition, participants whose median confidence judgement was equal to the maximum possible value were removed (9 participants). With some overlap between criteria, these procedures resulted in 12 participants being removed giving a remaining sample size of 29.

Confidence ratings were divided using a median split for each participant. This way of splitting the data was chosen due to potential differences in individual confidence overall. No constraints were placed on participant interpretation of the confidence scale, meaning that participants might map the confidence scale differently. By splitting the data by median, we can quantify how differences in confidence within participants affect serial dependence. These groups were further broken down by valid and false feedback to show the effect of false feedback on high confidence trials. This was done to determine any differential effects of feedback with different levels of confidence and to demonstrate the effects of confidence in isolation (valid feedback trials).

In another analysis aimed at investigating how relative differences in confidence affect serial dependence, data were split based on differences in confidence across trials. A negative confidence difference between the current and previous trial indicating lower confidence relative to the previous trial while a positive confidence difference indicated higher confidence relative to the previous trial. This analysis shows the effect of transitioning between different levels of relative confidence as opposed to the median split analysis which focussed on the effects of prior or current confidence in isolation. Predictions for these conditions are similar to the median split analysis. If observers are initially confident but then experience a relative decrease in confidence, the weight applied to initial decisions might be expected to increase, enhancing serial dependence. Conversely, if initial confidence is low, a relative gain in confidence could cause observers to down-weight previous observations, reducing serial dependence.

4.2.4.1. Model-Based Analysis

As in Chapter 2, a derivative of Gaussian (DoG) curve was fit to the moving average (window size of 20°) of participant errors conditioned on the difference between current trial and the previous trial. The amplitude parameter of the DoG curve was again taken to indicate the strength of serial dependence.

Permutation tests were used to assess the significance of the derived DoG amplitude values. The sign of data was inverted for a random subset of participants and curve fitting was repeated on this data. This procedure was repeated 10,000 times. The percentage of permutations producing amplitude values greater than the observed amplitude values was used to generate p-values.

To compare conditions permutation tests were performed on the difference between amplitude values (Fritsche, 2016). Permutations were created by randomly swapping condition labels within participants. Curve fitting was then performed on the pooled moving average in each condition. The difference between amplitude values for each condition was then calculated. 10,000 iterations of this procedure were performed. To generate p-values we took the proportion of values in the permutation distribution of greater magnitude than the observed difference.

4.2.4.2. Model-Free Analysis

To verify the results of the model-based analysis, a model-free approach (Samaha et al., 2019) was also used. This approach involves calculating the median participant error over two ranges which typically encompass serial dependence. First the error where the difference between successive stimuli is between 0° and -45° is calculated. This is then subtracted from the median error where the difference between successive stimuli is between 0° and 45°. This produces one value which indicates the overall serial bias for each participant. Positive values indicate assimilation whereas negative values show repulsion. Permutation tests were used to assess the significance of model free results as well as to compare conditions.

DoG fitting is used here due to its widespread uptake in the literature (Bliss et al., 2017; J. Fischer & Whitney, 2014; Pascucci et al., 2019). However, model-based analysis makes assumptions about data which may not always be met, particularly in the course of resampling procedures. Some iterations of the resampling procedure may produce poor model fits. For this reason, where model-based and model-free analyses differ in their conclusions, the model-free analysis may be the more reliable interpretation of the data.

All statistical analyses were carried out in Matlab.

4.2.4.3. Response-contingent analysis

Recent studies suggest that suggest that serial dependence is better quantified as an attractive effect between responses (Sadil et al., 2021; Sheehan & Serences, 2023). This could be because serial dependence is a decision-based phenomenon (Fritsche et al., 2017), or because responses are a better measure of stimulus perception (Sheehan & Serences, 2023). The results of Chapter 3 support the idea that serial dependence is better quantified from a response-contingent perspective.

There are additional reasons to prefer a response-based analysis in the case of the current data. Previous confidence levels may be associated with a difference in variability in responses. Low confidence responses are likely to exhibit greater variance than high confidence responses. The effect of differences in variability is that the derivative of Gaussian function used for analysis is effectively convolved with Gaussian functions of differing width (i.e. different variance) in different data groupings. This may lead to the false impression that a particular type of prior trial (one with greater variance) reduces serial dependence, as the DoG is convolved with a Gaussian of greater width, reducing DoG amplitude (G. K. Gallagher & Benton, 2022).

To avoid this spurious effect on serial dependence, a response-contingent analysis was utilised (Fritsche, 2016; G. K. Gallagher & Benton, 2022). This form of analysis treats the previous response as the value of the previous trial rather than the previous stimulus value. This eliminates any excess variability when calculating the difference between subsequent trials.

Data-correction techniques were applied to response-contingent data to remove oblique response biases which can produce the appearance of serial dependence (G. K. Gallagher & Benton, 2022; Pascucci et al., 2019). The same alternate-flip trial shuffling procedure applied in Chapter 2 was used as a control to assess the influence of spurious serial dependence arising from analysis (G. K. Gallagher & Benton, 2022). An oblique response bias can produce the appearance of serial dependence regardless of any actual relationship between trials. The shuffling procedure used reverses the order of even numbered trials to remove any temporal relationship between trials. The position of the first even numbered trial is swapped with the last, the second even trial is then swapped with the penultimate even trial. This is repeated for all even trials. Any spurious serial effect arising due to the oblique bias is not dependent on trial order and so should still be apparent in shuffled data. If the oblique bias correction is effective, then it should eliminate the appearance of serial dependence in this shuffled data.

4.3. Results

Participants generally performed well in the task (mean 0.71 correlation between stimulus and response, confidence interval [0.66, 0.75] standard deviation = 0.10). All conditions produced significant serial dependence, (all $p < 0.01$). The shuffled control analysis indicated that this was not an artefact of analysis (all shuffled $p > 0.1$).

4.3.1. Current confidence

Figure 4.3 shows derivative of Gaussian fits and Figure 4.4 shows bias values for both model-based and model-free forms of analysis for current decisions confidence. Current decision confidence did not produce significant differences in serial dependence with a one-tailed permutation test (current high confidence, $a = 2.81°$, model-free bias = 4.43° vs. current low confidence, $a = 2.48°$, model-free bias = 4.37°, DoG $p = .18$, model-free $p = .46$).

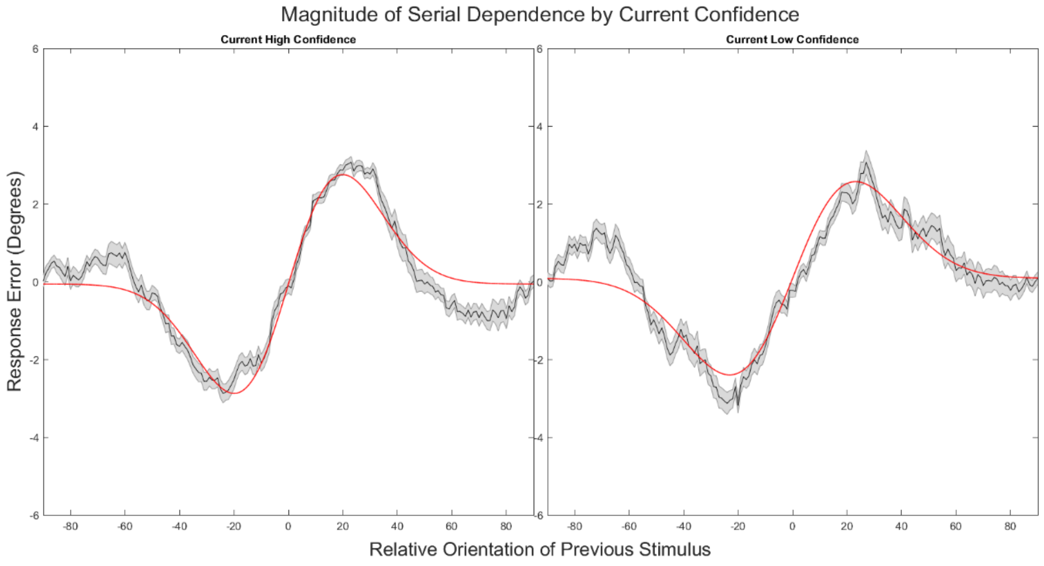

Figure 4.3. Derivative of Gaussian curve fits for data sorted by confidence in the current trial. Red line – DoG fit. Black line – moving average. Grey shading indicates standard error.

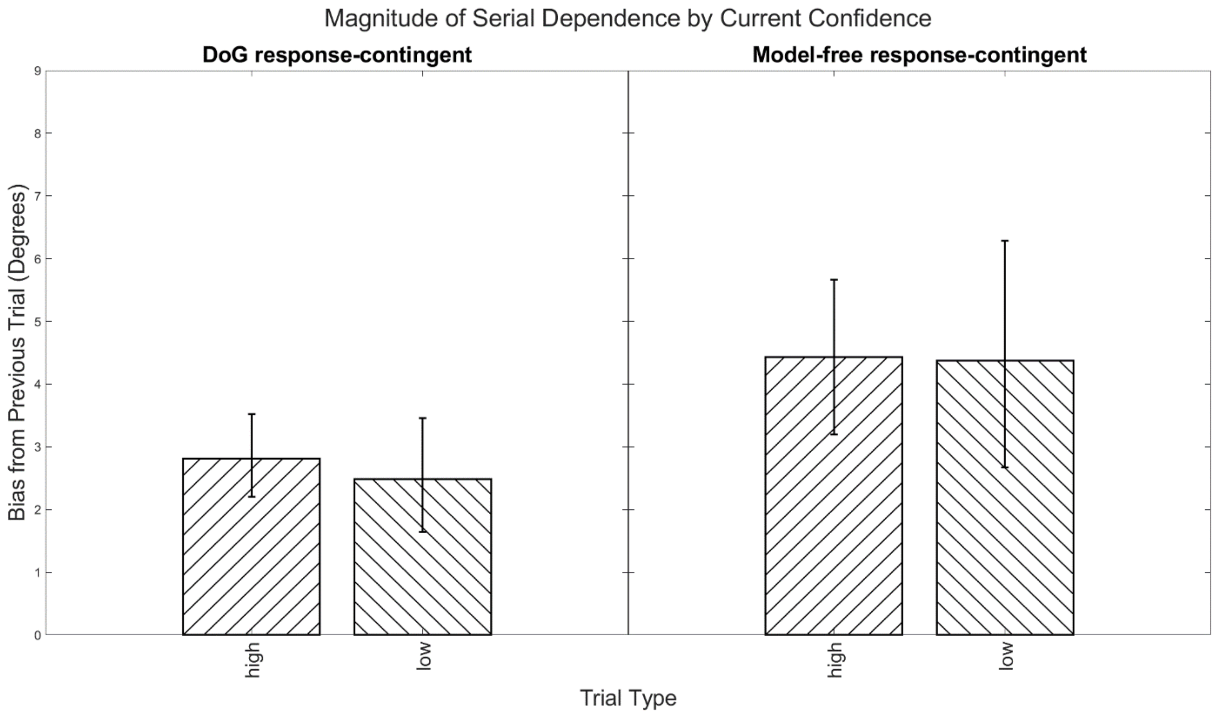

Figure 4.4. Magnitude of serial dependence for trials sorted by current confidence (high or low confidence. Left graph shows scale of serial dependence as assessed by derivative of Gaussian curve fitting. Values shown represent the amplitude of the curve. Right graph shows biases calculated using a model free approach.

4.3.2. Error feedback and Previous Confidence

Figure 4.5 shows derivative of Gaussian curve fits for previous confidence and feedback. Model-based and model-free bias values are shown in Figure 4.6. Valid vs. false feedback produced bias values which were significantly different (valid feedback, a = 3.07°, model-free bias = 5.00° vs. false feedback, a = 2.30°, model-free bias = 3.81°, DoG p = .01, model-free p = .02).

Previous experiments which did not provide feedback (Samaha et al., 2019; Suárez-Pinilla et al., 2018) suggest that prior confidence can dictate the strength of serial dependence. However, false feedback may influence the effect of confidence. When feedback is valid, prior high confidence is expected to enhance serial dependence compared to prior low confidence (Samaha et al., 2019; Suárez-Pinilla et al., 2018). A comparison of confidence levels when previous feedback was valid revealed a significant difference with a one-tailed permutation test (previous high confidence, valid feedback a = 3.80°, model-free bias = 5.90° vs. previous low confidence, valid feedback a = 2.52°, model-free bias = 4.15°, DoG p = .04, model-free p = .02). This suggests that previous confidence can dictate the strength of serial dependence.

The role of false negative feedback in this experiment was to reduce any effect of confidence. Therefore, it makes sense to consider the effect of feedback at differing levels of confidence. Negative feedback is not likely to have much of an effect when confidence is already low. However, when confidence is high, negative feedback would be expected to reduce confidence, with a resultant reduction in serial dependence. When results are broken down on the basis of previous confidence, the role of error feedback is apparent.

When previous judgements were made with high confidence, false feedback appeared to cause significant differences from judgements made with valid feedback (previous high confidence, valid feedback *a* = 3.80°, model-free bias = 5.90° vs. previous high confidence, false feedback *a* = 1.97°, model-free bias = 3.88°, DoG $p < .001$, model-free $p = .01$).

In contrast, when previous judgements were made with low confidence no significant difference was observed between valid and false feedback conditions (previous low confidence, valid feedback *a* = 2.52°, model-free bias = 4.15°, vs. previous low confidence, false feedback *a* = 2.80°, model-free bias = 3.88° DoG $p = .34$, model-free $p = .62$).

False feedback appears to reduce the effects of serial dependence so that high confidence false feedback trials are no longer significantly different from low confidence valid feedback trials (previous high confidence, false feedback *a* = 1.97°, model-free bias = 3.88° vs. previous low confidence, valid feedback *a* = 2.52°, model-free bias = 4.15°, DoG $p = .21$, model-free $p = .38$).

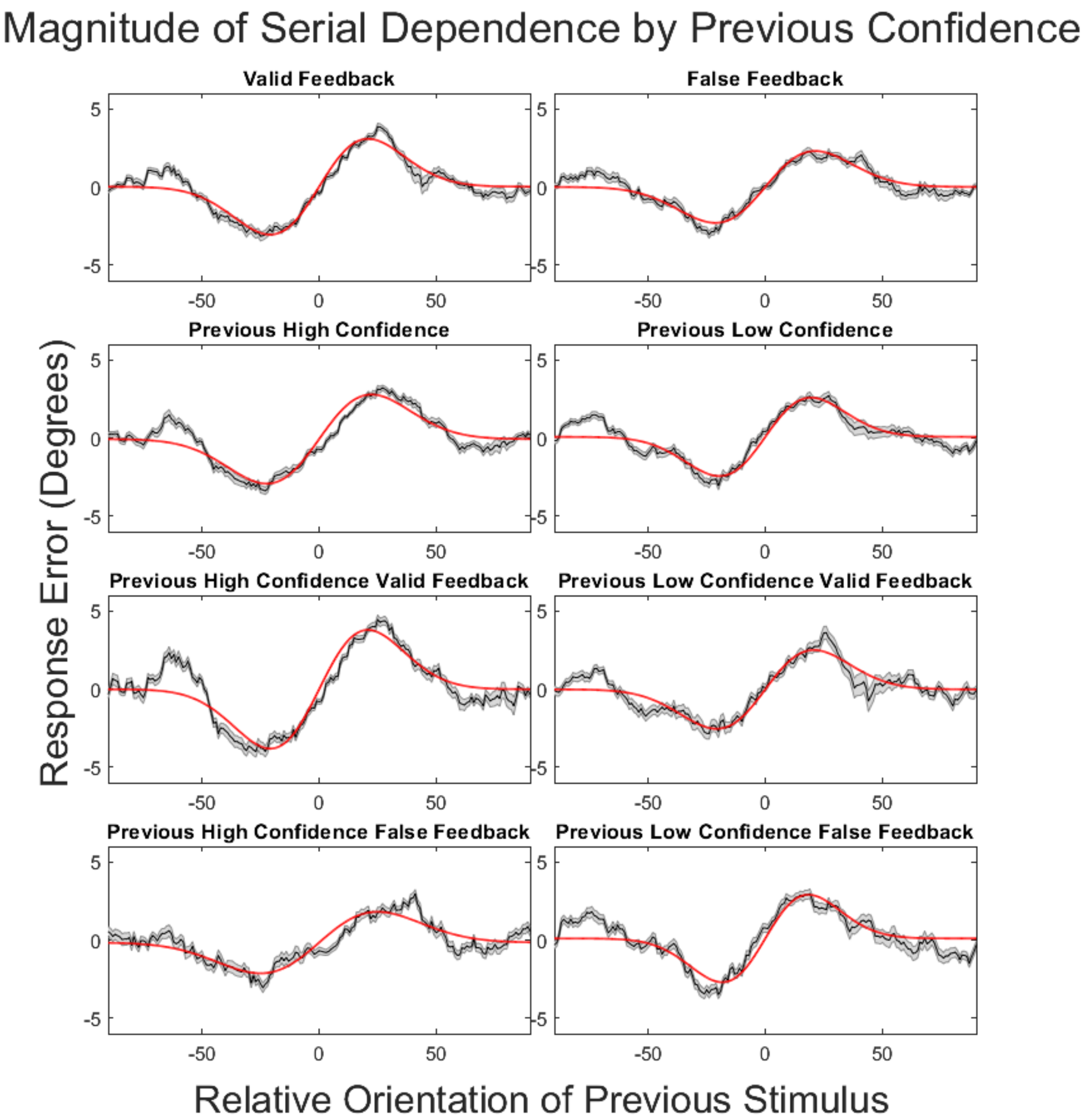

Figure 4.5. Derivative of Gaussian curve fits for data sorted by confidence in the previous trial. Red line – DoG fit. Black line – moving average. Grey shading indicates standard error.

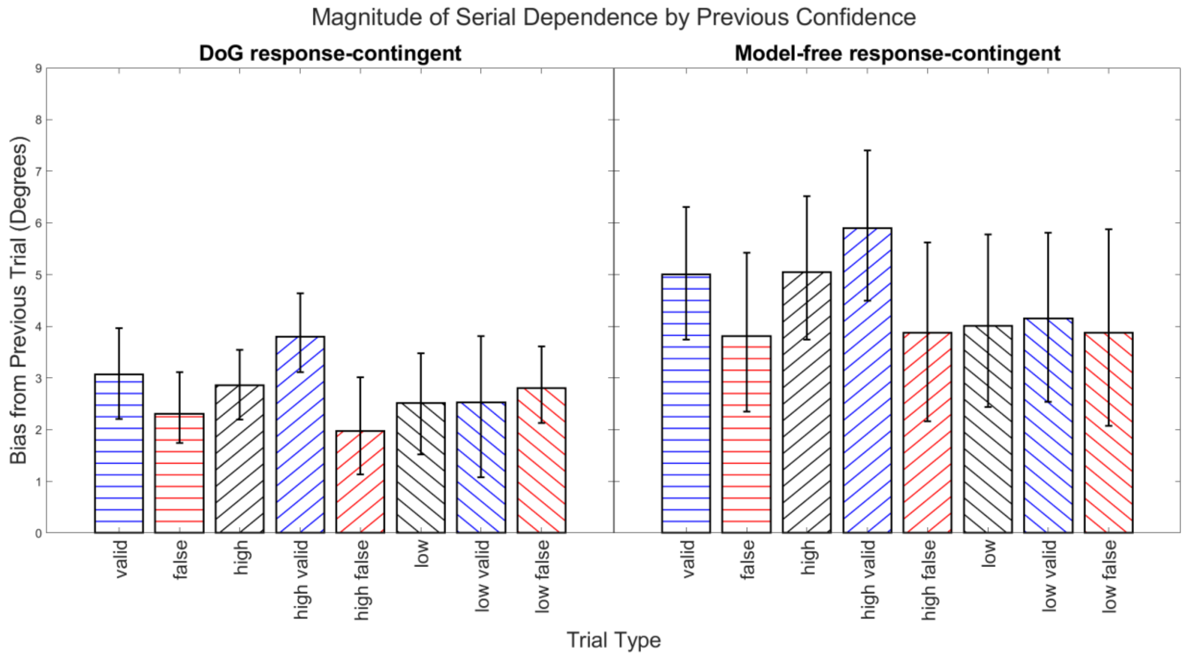

Figure 4.6. Magnitude of serial dependence for trials sorted by previous confidence (high or low confidence) and feedback type (false or valid feedback). Left graph shows scale of serial dependence as assessed by derivative of Gaussian curve fitting. Values shown represent the amplitude of the curve. Right graph shows biases calculated using a model free approach.

4.3.3. Reduced confidence vs. greater confidence

A relative difference in confidence could also impact participants' judgements, regardless of their initial level of confidence. For example, a low confidence judgement could still produce enhanced serial dependence if the following judgement was made with even lower confidence. To assess this possibility data were broken down by the relative difference in confidence level between trials. A negative sign to the difference indicated reduced confidence (Δ-negative) in the current trial relative to the previous whereas a positive sign indicated greater confidence in the current trial (Δ-positive).

Significant serial dependence was observed when participant confidence was higher on the current trial than the previous trial (Δ-positive a = 2.47; model-free bias = 4.08). A reduction in confidence on the current trial was also associated with significant serial dependence (Δ-negative $a = 2.94$, model-free bias = 4.92). A significant difference between these conditions was not evident (Δ-positive vs. Δ-negative, DoG $p = .12$, model-free $p = .12$). This holds true for trials with valid feedback, although a significant difference is suggested by model-based testing (Δ-positive, valid feedback vs. Δ-negative, valid feedback, DoG $p = .02$, model-free $p = .08$).

Higher confidence (Δ-positive) in the current trial resulted in significant serial dependence, with both valid and false feedback, when confidence was higher on the current trial (Δ-positive, false feedback $a = 2.28$, model-free bias = 3.96, Δ-positive, valid feedback $a = 2.58$ model-free bias = 4.32). The difference between false and valid feedback for current higher confidence trials was non-significant (Δ-positive, false feedback vs. Δ-positive, valid feedback, DoG $p = .29$ model-free $p = .30$)

Reduced confidence (Δ-negative) in the current trial with valid feedback produced significant serial dependence (Δ-negative, valid feedback $a = 3.78$, model-free bias = 5.97). Similarly, reduced confidence with false feedback also produced significant serial dependence (Δ-negative, false feedback $a = 2.21$ DoG $p < .001$ model-free bias = 3.97). The difference between these valid and false feedback was significant (Δ-negative, false feedback vs. Δ-negative, valid feedback, DoG $p = .02$ model-free $p < .01$). False feedback again caused the influence of reduced confidence to be negated, with reduced confidence false feedback trials producing serial dependence that was not significantly different from the serial dependence observed in greater confidence valid feedback trials (Δ-negative, false feedback vs. Δ-positive, valid feedback, DoG $p = .21$ model-free $p = .38$). Derivative of Gaussian fits for all transition data are shown in Figure 4.7. Model-based and model-free bias values are shown in Figure 4.8.

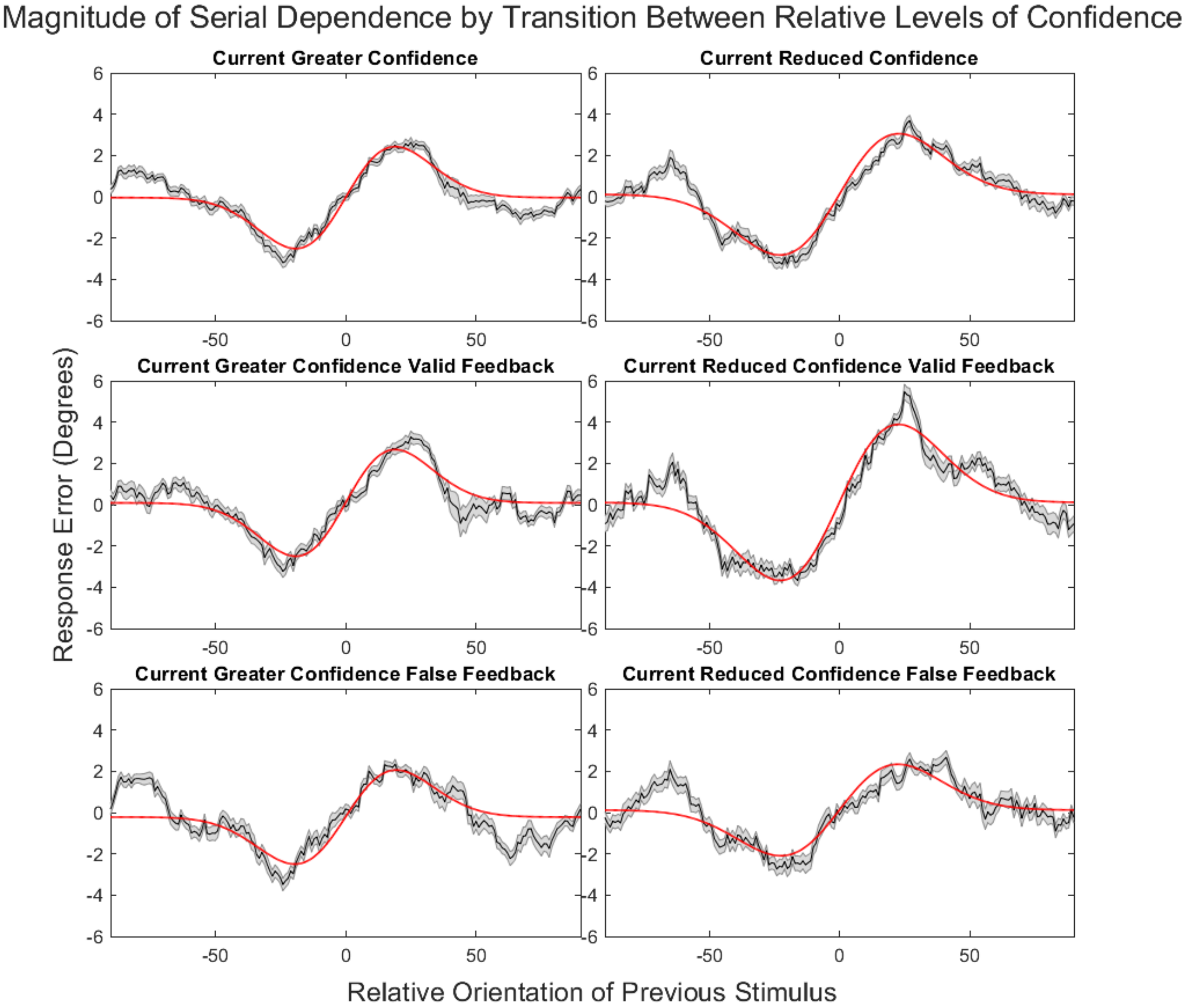

Figure 4.7. Derivative of Gaussian curve fits for data sorted by confidence in the previous trial. Red line – DoG fit. Black line – moving average. Grey shading indicates standard error

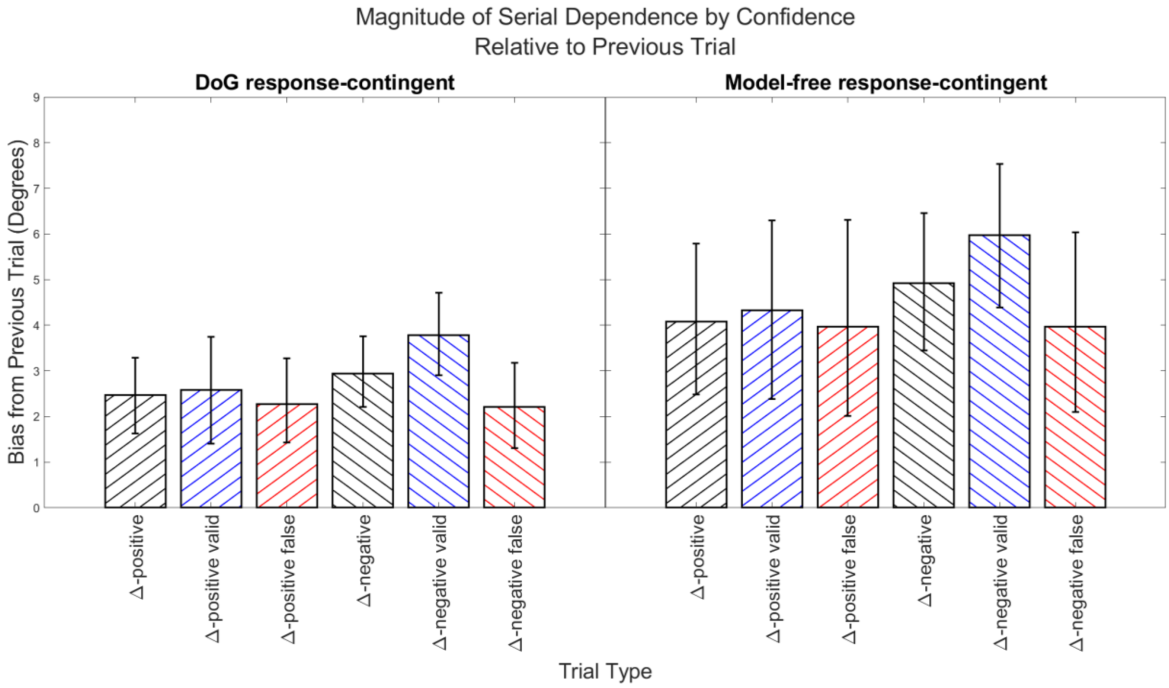

Figure 4.8. Magnitude of serial dependence for trials sorted by confidence relative to the previous trial (negative or positive chance in confidence) and feedback type (false or valid feedback). Left graph shows scale of serial dependence as assessed by derivative of Gaussian curve fitting. Values shown represent the amplitude of the curve. Right graph shows biases calculated using a model free approach.

4.3.4. Serial Effects in Confidence

Confidence judgements themselves may also exhibit serial effects (N. Mei et al., 2020; Rahnev et al., 2015; Suárez-Pinilla et al., 2018). To test this possibility, confidence distance values were regressed against previous confidence values. The correlation between current and prior confidence was moderate, although this varied across participants (mean Fisher-transformed correlation across participants = 0.41, confidence interval [0.33, 0.49] standard deviation = 0.16, converted to Cohen's d = 0.9169, one sample $t(28) = 10.95$, $p < .001$, correlations for each participant show in Figure 4.9).

As a form of control analysis resembling the shuffling approach used for orientation judgement serial dependence, the correlation between confidence judgements and reverseordered confidence judgements was carried out. This analysis produced no significant correlation (mean Fisher-transformed correlation across participants = -0.02, confidence interval [-0.09, 0.05] standard deviation = 0.12, one sample $t(28) = -.93$, $p = .35$.

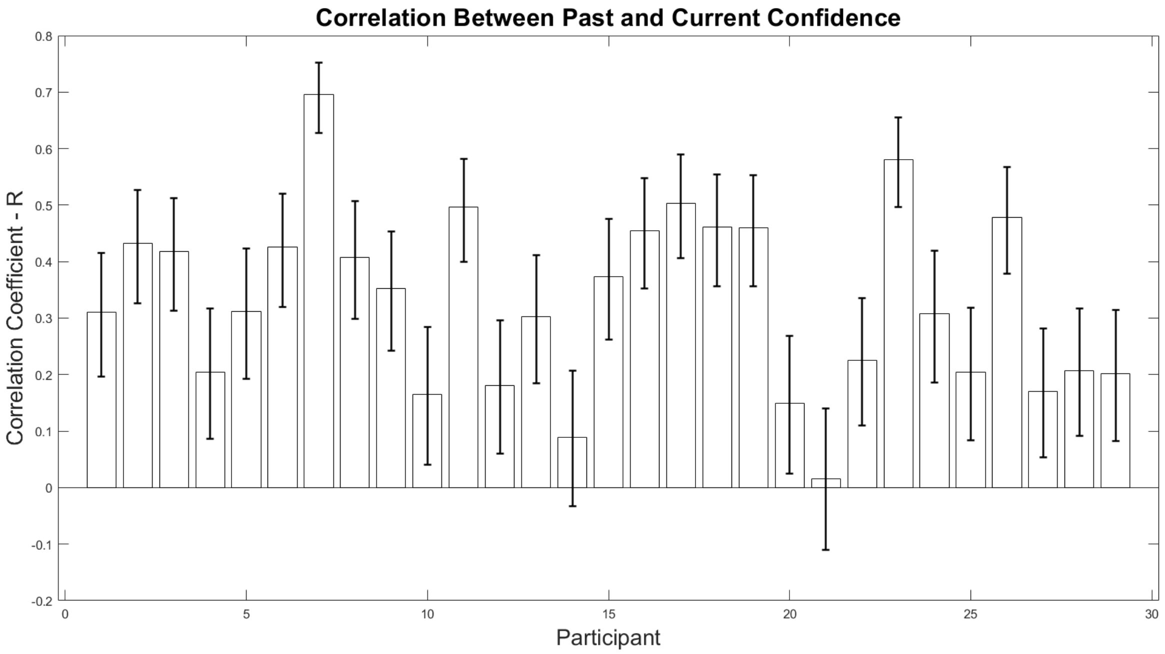

Figure 4.9. Correlation between previous and current confidence for each participant. Error bars represent 95% confidence intervals.

4.3.5. Role of Previous Error

We might expect confidence to be associated with errors (Ais et al., 2016; Fetsch et al., 2014; Samaha & Postle, 2017). To check that any observed effect of confidence was not simply an effect of prior errors we conducted a control analysis. Data were split by previous high or low error using a median split. Analysis yielded no significant differences between conditions (previous high error valid feedback, a = 3.11°, model-free bias = 5.40° vs. previous low error valid feedback, a = 2.98°, model-free bias = 4.98°, DoG p = .39, model-free p = .28). The effect of feedback on high confidence trials also supports the idea that this experiment does measure an effect of confidence rather than error. Confidence might be reduced by poor feedback while any effect of error in isolation should be unaffected by feedback.

The mean correlation between confidence ratings and errors was low (mean Fisher-transformed correlation across participants = -0.09, confidence interval [-0.12, -0.06] standard deviation = 0.08, converted to Cohen's d = -0.1895, one sample $t(28)$ = -5.99, p < .001, correlations for each participant show in Figure 4.10). Although this varied across individuals, the correlation generally followed the expected pattern of lower confidence with higher error. Earlier work suggests a coupling between confidence and error, the partial dissociation observed in the current experiment likely reflects procedural differences from other confidence tasks. In non-binary tasks confidence judgements may be less tightly coupled with error (Li & Ma, 2020).

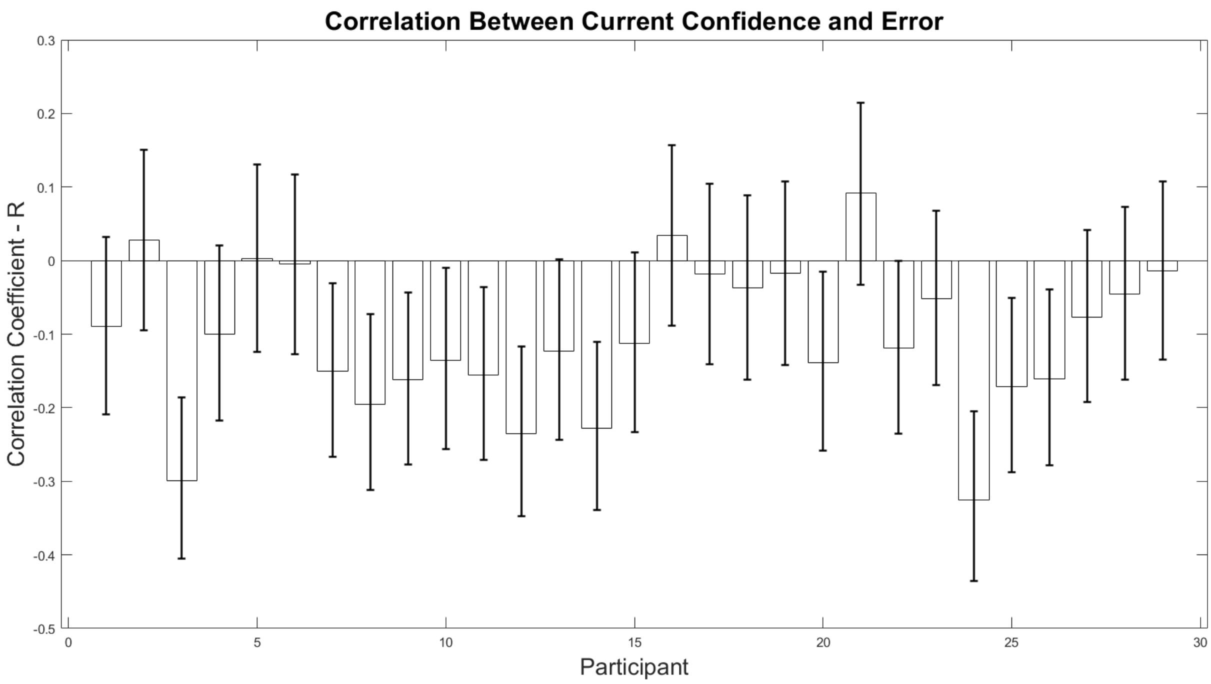

Figure 4.10. Correlation between current confidence and error for each participant. Error bars represent 95% confidence intervals.

4.4. Discussion

These results reaffirm the effect of subjective confidence on serial dependence. We observed that high confidence in previous stimuli appears to enhance serial dependence (when feedback is valid), in agreement with previous studies (Bosch et al., 2020; Samaha et al., 2019; Suárez-Pinilla et al., 2018). This effect of previous confidence was shown to be reduced with false feedback. Transitioning between relative levels of confidence (lower to higher confidence, Δ-positive vs. higher to lower confidence, Δ-negative) produced a similar result, suggesting that this was not an artefact of the median split. We did not observe an effect of current confidence on the strength of serial dependence.

Considering both objective measures of uncertainty, such as stimulus noise, in the current trial as well as subjective measures, such as previous trial confidence, might provide a fuller account of serial dependence which supports existing predictions. Previous studies have proposed a Bayesian basis for serial dependence (Cicchini et al., 2018; van Bergen & Jehee, 2019). According to this description of serial dependence, the strength of this effect should be weighted by the relative uncertainty in past and current stimuli. However, evidence for Bayesian models in experiments manipulating objective stimulus ambiguity has been limited, with only an effect of uncertainty in the current stimulus observed (Ceylan et al., 2021; G. K. Gallagher & Benton, 2022). In contrast, the current experiments and several other studies suggest serial dependence may be affected by subjective confidence in the previous stimulus (Samaha et al., 2019; Suárez-Pinilla et al., 2018). A synthesis of approaches could still reveal serial dependence to act according to Bayesian principles. Uncertainty in the previous trial judgement may be better summarised by confidence. On the other hand, if confidence arises from post-decisional processing (Balsdon et al., 2020; Hilgenstock et al., 2014; Pleskac & Busemeyer, 2010), uncertainty in the current stimulus can only rely on objective stimulus values prior to making a decision. A Bayesian model of serial dependence would therefore be forced to incorporate only objective uncertainty for the current stimulus but could include subjective confidence as a more detailed measure of uncertainty in the previous stimulus.

The lack of an observable effect of current confidence on serial dependence is consistent with this interpretation. Confidence may be formed alongside decisions (Dotan et al., 2018) or it could be produced by a post-decisional continuation of evidence accumulation (Balsdon et al., 2020; Hilgenstock et al., 2014; Pleskac & Busemeyer, 2010). In the current subjective confidence task, the confidence judgement was made simultaneously with the perceptual decision, however it is possible that participants performed perceptual and confidence judgements in sequence before responding. Post-decisional construction of confidence would not allow for current trial confidence to retroactively influence serial dependence; the perceptual decision which incorporates serial dependence would happen prior to formation of confidence.

If confidence does rely on post-decision evidence processing (Balsdon et al., 2020; Hilgenstock et al., 2014), then it could be a better measure of uncertainty in a previous stimulus than objective stimulus features such as noise. Further accumulation of evidence post-decision implies an improved assessment of uncertainty, which might be preferable to the first-pass processing of evidence which formed the basis of a perceptual decision. This may be why serial dependence is responsive to confidence when it is available but responsive to uncertainty prior to the availability of a confidence judgement.

However, it is also possible that the moderate serial effect observed in confidence judgements may have obscured effects of current confidence on perceptual serial dependence, assuming that this confidence autocorrelation represents a bias in response not related to subjective feelings of confidence. For example, if participant confidence was low but a high confidence response on the prior trial caused a repetition of a high confidence response, the current trial would appear to be made with high confidence. Current trials classified as low confidence trials might therefore include some high confidence trials, blurring any difference between current high and low confidence trials. However, if this autocorrelation reflects a genuine change in subjective confidence, then no such misassignment of confidence relationships should occur.

Furthermore, if misassignment was occurring, we might expect to observe differences in the Δ-positive or Δ-negative transitions which are not observed when sorting data by prior or current confidence in isolation. this is because these transitions are based on the sign of the difference between subsequent trials, rather than a median split. Any masking effects of a confidence judgement response bias might reduce the difference between subsequent trials but would be unlikely to change the sign of the difference. If a participant reported high confidence in one trial and then experienced low confidence in the following trial, a response bias in confidence judgement might cause them to report a level of confidence which would be classified as high in the median split analysis. However, although their reported confidence might be higher than their true feelings of confidence, it would not be higher than the confidence report on the initial trial. The difference between subsequent trials would still be negative and hence would be classified correctly in the analysis based on the sign of the transition (Δ-positive or Δ-negative). The consistency of median split and transition analyses suggests that any serial effect in confidence judgements was unlikely to be masking effects of current confidence.

It remains possible that feedback or confidence affect serial dependence in another way only indirectly related to uncertainty. Poor feedback could enhance attention on the following trial, reducing error. Low subjective confidence could act in exactly the same way; low confidence on one trial might promote increased attention or more effortful responses on the subsequent trial, reducing error. In both of these scenarios, the effect of negative evaluation of previous performance, either via feedback or confidence, is error reduction on the following trial. This is slightly different from an optimal combination of uncertainty in stimuli as described in Bayesian theories. In this case uncertainty in prior stimuli is instead acting indirectly via a process of directing mental resources.

Whether feedback affects serial dependence is a question in itself. Previous research has found an abolition of serial dependence with feedback in a motion judgement task (Fulvio et al., 2022). However, the binary feedback of Fulvio et al. might cause an extreme confidence judgement, either absolute certainty in the previous judgement or a near complete absence of confidence. The more subtle feedback used in the current experiment could instead result in reduced, but still present confidence. In real life situations feedback on a perceptual decision may be all-or-nothing as in the binary feedback used by Fulvio et al., or it could be a more subtle graded response, as in the current experiment. The study of Fulvio et al. and the current experiments are therefore complementary, but potentially distinct in terms of the decisions to which they are applicable.

Another potentially complementary result comes from Fornaciai and Park (2022). The authors found that feedback actually increased serial dependence following “correct” feedback, in contrast to the current study, which focuses on negative feedback. Fornaciai and Park hypothesised that this could be due to feedback acting as an additional source of information by which to weight previous stimuli, or it could act by affecting confidence in the prior judgement.

In general, feedback might be expected to minimise serial biases. Serial dependence constitutes an error on the part of the observer which would be communicated to them via feedback. This creates the possibility that participants in the current experiment could use feedback information to learn to minimise serial dependence. However, in this case feedback was unreliable in the long term; participants were not made aware of false feedback exaggerating the scale of their errors. This prevented participants from actively using this information to change their behaviour and prevent serial dependence over the course of the experiment.

Stimulus noise was intended to increase the plausibility of poor feedback, despite potential confidence in a decision. In combination with this noise-induced plausibility, the choice to make the chance of false feedback 50:50 was intended to prevent participants learning that feedback was unreliable. Essentially, if feedback sometimes seems incongruent with confidence in your decision, the presence of visual ambiguity makes it more believable that your interpretation of the stimulus was actually incorrect. A fifty percent chance of false feedback could be argued to reduce participant confidence in their understanding of the task. Nevertheless, participants generally performed well given the presence of noise in stimuli (mean 0.71 correlation between stimulus and response) suggesting that this did not occur.

The effects of feedback and confidence on serial dependence might reaffirm the idea that this bias is a decision-based effect rather than originating from a low-level perceptual system (Fritsche et al., 2017). However, it is worth noting that according to the account of decision inertia by Akaishi et al., errors on the previous trial should be associated with a greater tendency toward assimilation on the current trial (Akaishi et al., 2014). This is not evident in the current data, as the results of the control analysis indicate no difference between previous high error and previous low error trials. This suggests that decision inertia cannot account for the current data.

Notably, the definition of confidence used might influence how likely we think this is. If confidence is defined as the probability of decision accuracy (Pouget et al., 2016), then it necessarily requires a decision. The fact that confidence can affect serial dependence then suggests that post-perceptual decision factors may be involved in this assimilative bias.

Alternatively, confidence may also be thought of as an on-line process which can develop prior to a decision (Dotan et al., 2018). If confidence does evolve in tandem with evidence accumulation it might allow some wiggle room to consider non-decision theories of serial dependence. Some studies suggest that there are ways in which confidence might evolve alongside evidence accumulation and can even influence the process used to reach a perceptual decision (Balsdon et al., 2020; Kaanders et al., 2022; Lee et al., 2023). However, this sort of on-line confidence construction should allow an effect of current confidence on serial dependence, something that is not observed in the current data.

In conclusion, these results demonstrate that confidence in prior stimuli can influence the strength of serial dependence. Higher confidence in initial stimuli leads to enhanced serial dependence. In addition, negative feedback can reduce serial dependence following high confidence trials, suggesting that confidence was reduced by feedback. These results may point to a higher-level basis for serial dependence. The relationship of confidence to serial dependence may act in concert with the effects of current stimulus uncertainty, as outlined in Chapter 2, to allow serial dependence to conform to Bayesian predictions.

Chapter 5. General Discussion

5.1. Summary

In this thesis the role of uncertainty in determining the strength of serial dependence was explored. This was motivated by studies suggesting that serial dependence ought to be applied to perceptual decisions in a manner consistent with principles of Bayesian inference (Burr & Cicchini, 2014; Glasauer, 2019; van Bergen & Jehee, 2019). According to this idea, current and past information should be weighted by their associated uncertainty in order to make optimal decisions about the current state of the world. Serial dependence involves a blending of past and current stimulus information. Considering the uncertainty associated with these sources of information should dictate the strength of this assimilative bias.

Chapter 2 suggests that current stimulus uncertainty, characterised by noise present in a stimulus, is taken into consideration by the visual system when determining the strength of visual serial dependence. In experiments using orientation stimuli, higher uncertainty in the current stimulus was found to enhance serial dependence. No evidence was found for a role of prior stimulus uncertainty. This serves as partial evidence for serial dependence as a Bayesian process which weights information by its associated level of uncertainty.

In this chapter serial dependence was considered using the previous stimulus, or the previous response, as a measure of the orientation from the previous trial. This was done to rule out the possibility that high noise stimuli might just provoke more varied responses, which could cause the appearance of reduced serial dependence. From a stimulus-contingent perspective prior high noise appeared to reduce serial dependence. This effect was not apparent when stimuli were considered from a response-contingent perspective, suggesting that it was not a true effect of stimulus uncertainty. Response-contingent analysis has also been suggested to better reflect observer perception of stimuli (Fritsche, 2016) and so may be the more logical value to use when considering serial biases arising from the previous trial. This raises the question of whether serial dependence should be considered as an attraction to the prior response rather than to the prior stimulus.

Chapter 3 attempted to answer this question by presenting stimuli featuring an orientation midway between the prior stimulus orientation and the associated response orientation. This allowed the influence of prior stimulus and prior response on this midway stimulus to be easily differentiated. The results of this experiment suggest that serial dependence should be considered an attraction to the prior response rather than to the prior stimulus. This makes sense as observers generally do not have direct access to objective stimulus values and their responses may serve as a proxy for their actual perception of stimulus values. However, an attraction to prior response could also indicate that serial dependence is instead just an attraction between decisions. A decision on one trial might influence the next trial without any influence on perception; stimuli appear exactly the same to observers but the decisions they produce in response to those stimuli are altered. Other combinations of percept and decision could also be possible, percepts might be attracted to prior decisions, or current decisions to prior percepts.

The second experiment of Chapter 3 attempted to distinguish between attraction to prior decision or to prior percept. This was achieved by asking participants to complete a comparison task on each midway stimulus, asking them if these stimuli resembled either the prior stimulus or prior response. If prior percept was responsible for serial dependence, we would expect observers to report that midway stimuli look more like the previous response. Alternatively, if serial dependence was based on the prior decision then we would expect no clear preference for either prior stimulus or response. Although the results appeared to show a preference for prior response, indicating an attraction towards prior perception of stimuli, due to the procedure used this could also be interpreted as the result of low-level repulsion from the prior stimulus.

The finding that previous response provides the better measure of serial dependence informed the type of analysis used in the next chapter. Chapter 4 returns to the question of uncertainty, this time considering uncertainty from a subjective perspective. Confidence is used as a measure of uncertainty in this experiment. Consistent with earlier work, an effect of prior subjective uncertainty on serial dependence was observed. Greater confidence in initial responses enhanced serial dependence. False feedback was given after observer orientation judgements in order to manipulate observer confidence; the scale of participant error was magnified in order to reduce confidence. While high confidence in prior stimuli enhanced serial dependence, false feedback eliminated this effect. Low confidence trials showed reduced serial dependence, with false feedback having no effect. This suggests that prior high confidence can enhance serial dependence however, poor feedback can negate this effect of confidence. Current confidence was not found to have an effect on serial dependence.

The effect of subjective confidence in the prior trial is complementary to the observation in Chapter 2 that objective uncertainty (noise) in the current trial can affect serial dependence. A Bayesian account would predict that the optimal combination of prior and current uncertainty should affect serial dependence. If initial uncertainty is low compared to current higher uncertainty, then it makes sense to rely on previous information in determining the attributes of current stimuli. In this case, serial dependence may be a beneficial outcome. Alternatively, if initial uncertainty is high but current uncertainty is reduced the current information may be the more trustworthy data to rely on. In this case serial dependence should be reduced.

The results for objective uncertainty (noise) and subjective uncertainty (confidence) provide only limited evidence for this idea in isolation. However, if we consider them together then a clear example is provided of an optimal combination of uncertain data according to Bayesian inference. The measure of uncertainty considered in the current stimulus is limited to objective stimulus uncertainty, as no further information is available at the time of a decision. In contrast, when considering uncertainty in the prior stimulus, subjective confidence can also be taken into account. The combination of these two forms of uncertainty can allow for the optimal application of serial dependence. Initial high confidence can enhance serial dependence while current low stimulus noise can reduce serial dependence.

Why then do we not find evidence of these two forms of uncertainty contributing to a Bayesian strategy in isolation? This may be because of the nature of confidence construction. Confidence may be produced after a decision is made (Balsdon et al., 2020; Hilgenstock et al., 2014; Pleskac & Busemeyer, 2010). Essentially, an observer might calculate the value of an attribute and then further consideration of evidence determines how confident they are in their decision. Importantly, serial dependence is present in the observer's decision. This means that serial dependence affects a decision prior to current confidence construction. Current confidence could not retroactively influence serial dependence. The only measure of uncertainty in current stimuli accesible at the time of a decision is objective stimulus uncertainty.

If confidence does arise from a continuation of the evidence accumulation process, then this might imply that it provides a better account of uncertainty than the initial evidence accumulation used to reach a decision. The weighting of previous information may take into account subjective confidence, as post-decision this better-considered information is available to the visual system. However, at the time of a decision, confidence information is not yet available. Objective stimulus uncertainty is part of the evidence collection that contributes to a perceptual decision. This form of uncertainty could therefore contribute to evidence weighting in the current decision. This accounts for the lack of an effect of prior stimulus uncertainty observed in Chapter 2, and other experiments (Ceylan et al., 2021).

There are theoretical reasons to believe that serial dependence might arise from a Bayesian mechanism. The predictions of a Bayesian sequential updating process resemble the pattern of responses observed in serial dependence studies (Glasauer, 2019). In addition, use of the Kalman filter (which can be thought of as a Bayesian updating strategy incorporating the normality assumption) has been employed as an effective descriptive model of serial dependence (Burr & Cicchini, 2014; Kalm & Norris, 2018). The results included in this thesis provide evidence that Bayesian sequential updating is a plausible mechanism dictating the application of serial dependence.

5.2. Limitations Of Experiments

One potential limitation of all of the experiments included in this thesis is that they rely on adjustment tasks. This means that the results obtained might differ with other experimental paradigms such as two alternative forced choice approaches (Pascucci et al., 2023). However, some studies using different methodologies have produced results consistent with the conclusions of the current experiments (for confidence: Bosch et al., 2020; for objective stimulus uncertainty: Cicchini et al., 2018).

In addition, all experiments included in this thesis use orientation stimuli. Serial dependence can vary in its application across stimulus types so it remains possible that different stimulus types might induce different behaviour. However, studies using other stimuli demonstrate similar results. Complementary results for the influence of current stimulus uncertainty have been observed using face stimuli (Lidström, 2019). In addition, similar results for the influence of confidence have been observed using random dot kinetograms (Bosch et al., 2020; Suárez-Pinilla et al., 2018).

Ambiguous results from the second experiment of Chapter 3 leave it unclear if serial dependence represents an attraction to prior percept or decision. The binary task options featuring orientations either side of the midway stimulus orientation meant that the observed results could be explained by attraction towards the prior response or repulsion from the prior stimulus. Repeating this experiment with procedures designed to minimise repulsive adaptation might provide clearer results. This might be done by rotating stimuli around the screen between trials in a similar way to the procedures of Chapters 2 and 4. This would require careful positioning of previous stimulus- and response-adjacent comparison stimuli so that they do not overlap with any previously presented stimuli. These stimuli could instead be presented at points along the radius stretching from the fixation circle towards the point of adjustment stimulus presentation. However, this would produce differences in peripheral position of stimuli which might also affect serial dependence (Manassi et al., 2019). However, some research does suggest that eccentricity does not affect serial dependence (Suárez-Pinilla et al., 2018).

5.3. Future Experiments

A direct test of the idea that stimulus uncertainty and confidence are combined in a Bayesian manner could involve both stimulus noise manipulations and confidence judgements in the same experiment. The main issues with this approach are logistical; a large number of trials would be needed to produce the necessary combinations of all stimulus manipulations and confidence measurements. This may be particularly difficult as differences in stimulus noise are likely to be associated with differences in confidence. The finding that poor feedback can negate the effect of high confidence in the prior trial might mitigate this to a degree, allowing for low noise, low confidence trials. Similarly, complementary findings involving the use of positive feedback might allow for high noise, high confidence trials (Fornaciai & Park, 2022).

However, no similar intervention is available for altering the effects of confidence in the current trial.

The suggested combination of uncertainty measures in prior and current trials hinges on the idea that confidence is constructed post-decision (Balsdon et al., 2020; Hilgenstock et al., 2014; Pleskac & Busemeyer, 2010). This explanation might also imply that serial dependence is a decision-based effect as confidence by some definitions requires a decision be made. Notably other ideas about confidence construction do exist in the literature. Online confidence calculation has been described, with confidence developing alongside evidence accumulation (Dotan et al., 2018) and it has been suggested that decisions might even be determined by confidence (Lee et al., 2023). These alternative interpretations of confidence might be expected to allow confidence to have an influence on current decisions, as the time course of confidence development would now be placed prior to the perceptual decision which is being affected by serial dependence. For this reason, an effect of this form of confidence would also undermine the idea that an effect of confidence affirms a decision basis for serial dependence. A future experiment should explore this.

Work investigating the role of confidence in serial dependence has required a direct report of observer confidence. This comes with the potential pitfall of requiring observers to consider confidence information as part of their judgement. It could be the case that observers incorporate confidence into their perceptual decisions because they were asked to consider their confidence. Other less direct methods of measuring confidence, such as post-decision wagering, might still induce consideration of confidence, if only implicitly. A better approach might be to measure observer confidence in the absence of any direct report. This might involve proxy measures for confidence which are quantifiable without requiring observer responses, such as changes in pupil dilation (Balsdon et al., 2020; Lempert et al., 2015) or neural correlates of confidence magnitude (Geurts et al., 2022; Rausch et al., 2020).

5.4. Conclusion

The results presented in this thesis constitute evidence that serial dependence is compatible with Bayesian interpretations. This assimilative bias can be best characterised as an attractive bias towards the prior response. It remains unclear whether this attraction to response reflects an attraction between decisions or an attraction to the prior percept. However, the evident effect of confidence could be taken to imply the necessity of decisions. If confidence is defined as the perceived probability that a decision is correct, then confidence construction must logically come after a decision has been made. The ability of confidence to affect serial dependence implies that prior decisions are necessary.

Serial dependence has been proposed to constitute a method of noise reduction in perceptual decisions. Incorporating measures of uncertainty according to a Bayesian model would allow for the optimal application of this effect, which might otherwise produce unnecessary errors. The identified roles of prior confidence and current stimulus uncertainty in determining the strength of serial dependence demonstrate that this attractive bias can operate in a manner predicted by Bayesian theories. This further validates the idea that, despite producing errors, serial dependence is a useful feature of the visual system which can be flexibly applied based on rational principles to maintain stable visual perception.

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Van der Burg, E., Toet, A., Brouwer, A.-M., & van Erp, J. B. F. (2022). Sequential Effects in Odor Perception. *Chemosensory Perception*, *15*(1), 19–25. https://doi.org/10.1007/s12078-021-09290-7

Van Geert, E., Moors, P., Haaf, J., & Wagemans, J. (2022). Same stimulus, same temporal context, different percept? Individual differences in hysteresis and adaptation when perceiving multistable dot lattices. *I-Perception*, *13*(4), 20416695221109300. https://doi.org/10.1177/20416695221109300

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Yu, J.-M., & Ying, H. (2021). A general serial dependence among various facial traits: Evidence from Markov Chain and derivative of Gaussian. *Journal of Vision*, *21*(13), 4. https://doi.org/10.1167/jov.21.13.4

Zhang, H., & Alais, D. (2020). Individual difference in serial dependence results from opposite influences of perceptual choices and motor responses. *Journal of Vision*, *20*(8), 2. https://doi.org/10.1167/jov.20.8.2

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Appendices

Appendix A

Table A1. Recent publications exploring serial dependence in different stimulus types.

STIMULUS TYPE	PUBLICATION REFERENCE
NUMEROSITY	Fornaciai, M., Park, J., (2020) Attractive serial dependence between memorized stimuli. Cognition,200.
	Togoli, I., Fedele, M., Fornaciai, M., Bueti, D., (2021). Serial dependence in time and numerosity perception is dimension-specific. Journal of vision, 21(5), 6. https://doi.org/10.1167/jov.21.5.6
	Fornaciai, M., Park, J., (2022). The effect of abstract representation and response feedback on serial dependence in numerosity perception. Attention, perception & psychophysics, 10.3758/s13414-022-02518-y. Advance online publication. https://doi.org/10.3758/s13414-022-02518-y
MONETARY VALUE	Morimoto, Y., & Makioka, S. (2022). Serial dependence in estimates of the monetary value of coins. Scientific reports, 12(1), 20212. https://doi.org/10.1038/s41598-022-24236-z
CAUSALITY	Deodato, M., Melcher, D. (2022). The effect of perceptual history on the interpretation of causality. Journal of vision, 22(11), 13. https://doi.org/10.1167/jov.22.11.13
AUDITORY	Arzounian, D., de Kerangal, M., de Cheveigné, A., (2017). Sequential dependencies in pitch judgments. The Journal of the Acoustical Society of America. 142. 3047-3057.
	Ho, H.T., Burr, D.C., Alais, D., and Morrone, M.C. (2019). Auditory perceptual history is propagated through alpha oscillations. Curr. Biol. 29, 4208–4217.e3.
	Motala, A., Zhang, H., Alais, D., (2020). Auditory Rate Perception Displays a Positive Serial Dependence. i-Perception, 11(6), 2041669520982311. https://doi.org/10.1177/2041669520982311
ODOR PERCEPTION	Van der Burg, E., Toet, A., Brouwer, A.-M., van Erp, J. B. F. (2021). Sequential effects in odor perception. Chemosensory Perception, (20210626). https://doi.org/10.1007/s12078-021-09290-7
FACIAL AGE	Clifford, C.W.G., Watson, T.L., White, D., (2018) Two sources of bias explain errors in facial age estimation. R. Soc. open sci. 5: 180841. http://dx.doi.org/10.1098/rsos.180841
	Manassi, M., Whitney, D., (2022). Illusion of visual stability through active perceptual serial dependence. Science advances, 8(2), eabk2480. https://doi.org/10.1126/sciadv.abk2480
FACIAL IDENTITY	Turbett, K., Jeffery, L., Bell, J., Burton, J., Palermo, R., (2021). Autistic Traits are Associated with Less Precise Perceptual Integration of Face Identity. Journal of autism and developmental disorders, 10.1007/s10803-021-05111-8. Advance online publication. https://doi.org/10.1007/s10803-021-05111-8
	Kim, S., Alais, D., (2021) Individual differences in serial dependence manifest when sensory uncertainty is high, Vision Research, 188: 274-282.

	Turbett, K., Jeffery, L., Bell, J., Digges, A., Zheng, Y., Hsiao, J., & Palermo, R. (2021). Serial Dependence of Facial Identity for Own- and Other-Race Faces. Quarterly Journal of Experimental Psychology. https://doi.org/10.1177/17470218211059430
EMOTIONAL EXPRESSION	Shen-Mou, H., Zhao-Rong, W., (2019) The roles of preceding stimuli and preceding responses on assimilative and contrastive sequential effects during facial expression perception. Cognition and Emotion. DOI: 10.1080/02699931.2019.1696752
	Alais, D., Xu, Y., Wardle, S. G., Taubert, J. (2021). A shared mechanism for facial expression in human faces and face pareidolia. Proceedings of the Royal Society B, 288(1954), 20210966–20210966. https://doi.org/10.1098/rspb.2021.0966
	Van der Burg, E., Toet, A., Brouwer, A. M., Van Erp, J., (2021). Serial Dependence of Emotion Within and Between Stimulus Sensory Modalities. Multisensory research, 1–22. Advance online publication. https://doi.org/10.1163/22134808-bja10064
BODY SIZE	Alexi, J., Cleary, D., Dommisse, K., Palermo, R., Kloth, N., Burr, D., Bell, J.C. (2017). Past visual experiences weigh in on body size estimation. Scientific Reports. 8 (215).
	Alexi, J., Palermo, R., Rieger, E., Bell, J., (2019). Evidence for a perceptual mechanism relating body size misperception and eating disorder symptoms. Eat Weight Disord https://doi.org/10.1007/s40519-019-00653-4
PERCEIVED GENDER AND BEAUTY	Kramer, R. S. S., & Pustelnik, L. R. (2021). Sequential effects in facial attractiveness judgments: separating perceptual and response biases. Visual Cognition, 1-10, 1–10. https://doi.org/10.1080/13506285.2021.1995558
	Kramer, R.S.S., Jones, A.L., (2020). Sequential effects in facial attractiveness judgments using cross-classified models: investigating perceptual and response biases. Journal of Experimental Psychology: Human Perception and Performance, 46(12), 1476–1489. https://doi.org/10.1037/xhp0000869
	Yu, J.-M., Ying, H., (2021). A general serial dependence among various facial traits: evidence from markov chain and derivative of gaussian. Journal of Vision, 21(13), 4–4. https://doi.org/10.1167/jov.21.13.4
AESTHETICS	Kim, S., Burr, D., Alais, D., (2019) Attraction to the recent past in aesthetic judgments: A positive serial dependence for rating artwork. Journal of Vision. 19(12):19. doi: 10.1167/19.12.19.
ORIENTATION	Kondo, A., Murai, Y., Whitney, D., (2022). The test-retest reliability and spatial tuning of serial dependence in orientation perception. Journal of Vision, 22(4), 5–5. https://doi.org/10.1167/jov.22.4.5
	Galluzzi, F., Benedetto, A., Cicchini, G. M., & Burr, D. C. (2022). Visual priming and serial dependence are mediated by separate mechanisms. Journal of Vision, 22(10), 1–1. https://doi.org/10.1167/jov.22.10.1
	Abreo, S., Gergen, A., Gupta, N., & Samaha, J. (2023). Effects of satisfying and violating expectations on serial dependence. Journal of Vision, 23(2), 6–6. https://doi.org/10.1167/jov.23.2.6
POSITION	Stein, H., Barbosa, J., Rosa-Justicia, M., Prades, L., Morató, A., Galan, A., Ariño, H., Martinez-Hernandez, E., Castro-Fornieles, J., Dalmau, J., Compte, A., (2019) Disrupted serial dependence suggests deficits in synaptic potentiation in anti-NMDAR encephalitis and schizophrenia. doi:10.1101/830471. PPR:PPR102658.
	Feigin, H., Baror, S., Bar, M., Zaidel, A., (2021). Perceptual decisions are biased toward relevant prior choices. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-020-80128-0
	Luo, M., Zhang, H., Luo, H., (2022). Cartesian coordinates scaffold stable spatial perception over time. Journal of Vision, 22(8), 13–13. https://doi.org/10.1167/jov.22.8.13

SCENE PERCEPTION	Manassi, M., Liberman, A., Chaney, W., Whitney, D. (2017). The perceived stability of scenes: Serial dependence in ensemble representations. Scientific Reports, 7(1): 1971, https://doi.org/10.1038/s41598-017-02201-5
VARIANCE	Suárez-Pinilla, M., Seth, A. K., Roseboom, W. (2018). Serial dependence in the perception of visual variance. Journal of Vision, 18(7), 4. http://doi.org/10.1167/18.7.4
SIZE/DURATION	Ellinghaus, R., Gick, M., Ulrich, R., Bausenhart, K. M., (2019). Decay of internal reference information in duration discrimination: Intertrial interval modulates the Type B effect. Quarterly journal of experimental psychology (2006), 72(6), 1578–1586. https://doi.org/10.1177/1747021818808187
	Wehrman, J.J., Wearden, J., Sowman, P., (2020) Decisional carryover effects in interval timing: Evidence of a generalized response bias. Atten Percept Psychophys. https://doi.org/10.3758/s13414-019-01922-1
	Glasauer, S., Shi, Z., (2022). Individual beliefs about temporal continuity explain variation of perceptual biases. Scientific reports, 12(1), 10746. https://doi.org/10.1038/s41598-022-14939-8
TIMING PERCEPTION	Roseboom, W., (2018) Serial dependence in timing perception. Journal of Experimental Psychology: Human Perception and Performance. 45(1): 100–110. ISSN 0096-1523
	Bilacchi, C. M., Sirius, E., Cravo, A. M., de Azevedo Neto, R. M., (2021). Temporal dynamics of implicit memory underlying serial dependence. Memory & cognition, 10.3758/s13421-021-01221-x. Advance online publication. https://doi.org/10.3758/s13421-021-01221-x
MOTION	de Azevedo Neto R.M., Bartels A., (2021) Disrupting short-term memory in premotor cortex affects serial dependence in visuomotor integration. bioRxiv. DOI: 10.1101/2021.02.18.431802.
	Tschiersch M. (2022). Causal evidence for the higher-order origin of serial dependence suggests a multi-area account. Journal of neurophysiology, 128(2), 336–338. https://doi.org/10.1152/jn.00048.2022
	Zeljko, M., Grove, P. M., (2021). The effects of recent perceptual history on stream-bounce perception. Journal of experimental psychology. Human perception and performance, 47(6), 795–809. https://doi.org/10.1037/xhp0000916
EYE GAZE DIRECTION	Alais, D., Kong, G., Palmer, C., Clifford C., (2018) Eye gaze direction shows a positive serial dependency. Journal of Vision. 18(4):11. doi: 10.1167/18.4.11.
	Little, Z., Palmer, C., Susilo, T., (2022) Normal Gaze Processing In Developmental Prosopagnosia. Cortex. https://doi.org/10.1016/j.cortex.2022.05.011.
EYE CONTACT	Palmer, C. J., Bracken, S. G., Otsuka, Y., & Clifford, C. W. G. (2022). Is there a ‘zone of eye contact’ within the borders of the face? Cognition, 220. https://doi.org/10.1016/j.cognition.2021.104981
CONFIDENCE	Rahnev, D., Koizumi, A., McCurdy, L.Y., D’Esposito, M., Lau, H., (2015) Confidence leak in perceptual decision making. Psychol. Sci. 26, 1664–1680. (doi:10.1177/ 0956797615595037)
	Mei, N., Rahnev, D., & Soto, D. (2023). Using serial dependence to predict confidence across observers and cognitive domains. Psychonomic bulletin & review, 10.3758/s13423-023-02261-x. Advance online publication. https://doi.org/10.3758/s13423-023-02261-x
BIOLOGICAL MOTION	Chaney, W., Liberman, A., Whitney, D., (2016) Serial dependence in perception of biological motion. Journal of Vision;16(12):274. doi: 10.1167/16.12.274.
COLOUR	Barbosa, J., Compte, A., (2018) Build-up of serial dependence in color working memory. Scientific Reports (Nature Publisher Group) 10 (1)
SHAPE	Manassi, M., Kristjánsson, Á., Whitney, D., (2019). Serial dependence in a simulated clinical visual search task. Scientific reports, 9(1), 19937. doi:10.1038/s41598-

	019-56315-z
	Collins, T., (2021). Serial dependence occurs at the level of both features and integrated object representations. Journal of experimental psychology. General, 10.1037/xge0001159. Advance online publication. https://doi.org/10.1037/xge0001159
	Collins, T. (2022). Serial dependence tracks objects and scenes in parallel and independently. Journal of Vision, 22(7), 4–4. https://doi.org/10.1167/jov.22.7.4
NOVELTY	van Kesteren, M.T.R., de Vries, L., Meeter, M., (2019) Seeing the past: afterglow effects on familiarity judgments are category-specific. Learn. Mem. 26(7): 229-234.
SIZE	Kristensen, S., Fracasso, A., Dumoulin, S., Almeida, J., Harvey, B., (2021). Size constancy affects the perception and parietal neural representation of object size. NeuroImage. 232. 117909. 10.1016/j.neuroimage.2021.117909.
	Tong, K., Dubé, C., (2022). A tale of two literatures: a fidelity-based integration account of central tendency bias and serial dependency. Computational Brain & Behavior, (20220103). https://doi.org/10.1007/s42113-021-00123-0
HEADING	Feigin, H., Shalom-Sperber, S., Zachor, D. A., Zaidel, A., (2021). Increased influence of prior choices on perceptual decisions in autism. eLife, 10, e61595. https://doi.org/10.7554/eLife.61595
	Xu, L. H., Sun, Q., Zhang, B., Li, X. (2022). Attractive serial dependence in heading perception from optic flow occurs at the perceptual and postperceptual stages. Journal of vision, 22(12), 11. https://doi.org/10.1167/jov.22.12.11
	Wang, X.-Y., Gong, X.-M., Sun, Q., & Li, X. (2022). Attractive effects of previous form information on heading estimation from optic flow occur at perceptual stage. Journal of Vision, 22(12). https://doi.org/10.1167/jov.22.12.18
HEADING MEDICAL IMAGING	Manassi, M., Ghirardo, C., Canas-Bajo, T., Ren, Z., Prinzmetal, W., Whitney, D., (2021). Serial dependence in the perceptual judgments of radiologists. Cognitive research: principles and implications, 6(1), 65. https://doi.org/10.1186/s41235-021-00331-z
FOOD APPRAISAL	Van der Burg, E., Toet, A., Abbasi, Z., Brouwer, A.-M., Van Erp, J. B. F., Kallen, V. L., Kaneko, D., Kim, Y. (E., Kinnear, M., de Kock, H. L., Kusbiantari, D., Lee, T.-R., Liu, Y., Luhovyy, B. L., MacEachern, E., Mezgebe, A. G., Nikolova, R., Olatunde, G., Srisayekti, W., … Yürek, M. A. (2021). Sequential dependency for affective appraisal of food images. Humanities and Social Sciences Communications, 8(1). https://doi.org/10.1057/s41599-021-00909-4

Appendix B

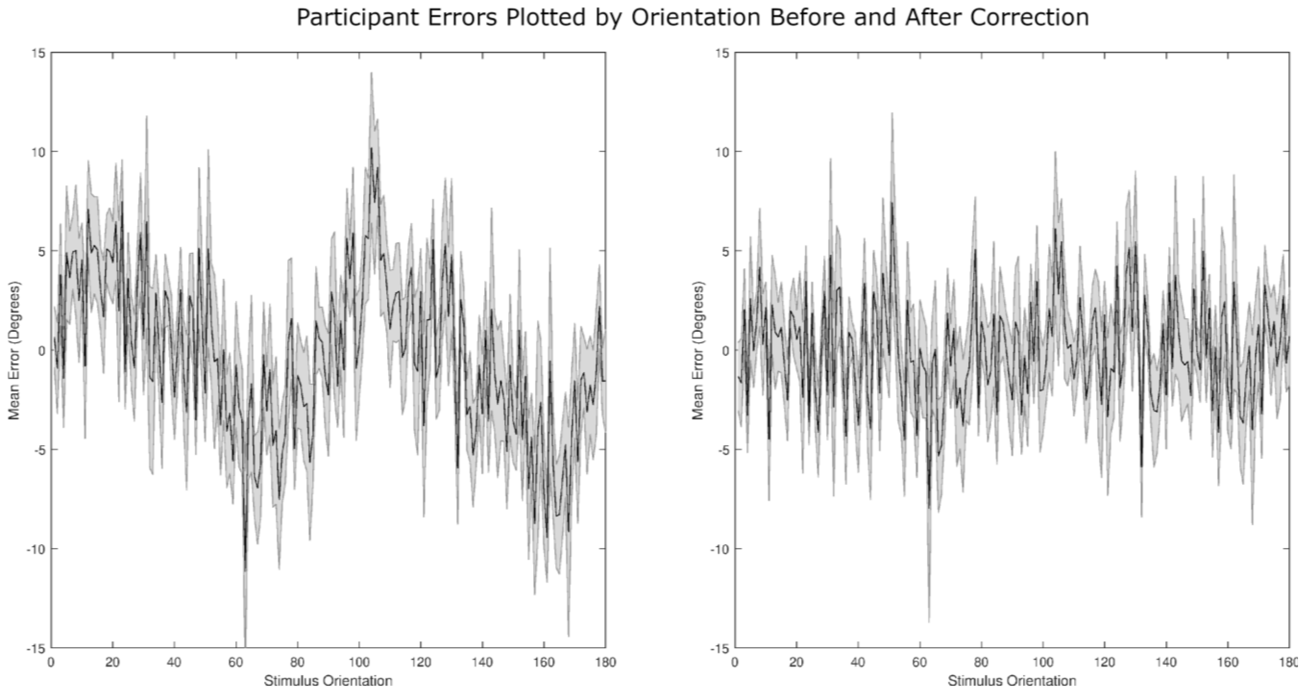

Figure B1. Response errors across stimulus orientations before and after correction for oblique response bias. Left graph shows errors pooled across participants before correction. Right graph shows the same data post-correction.

Appendix C

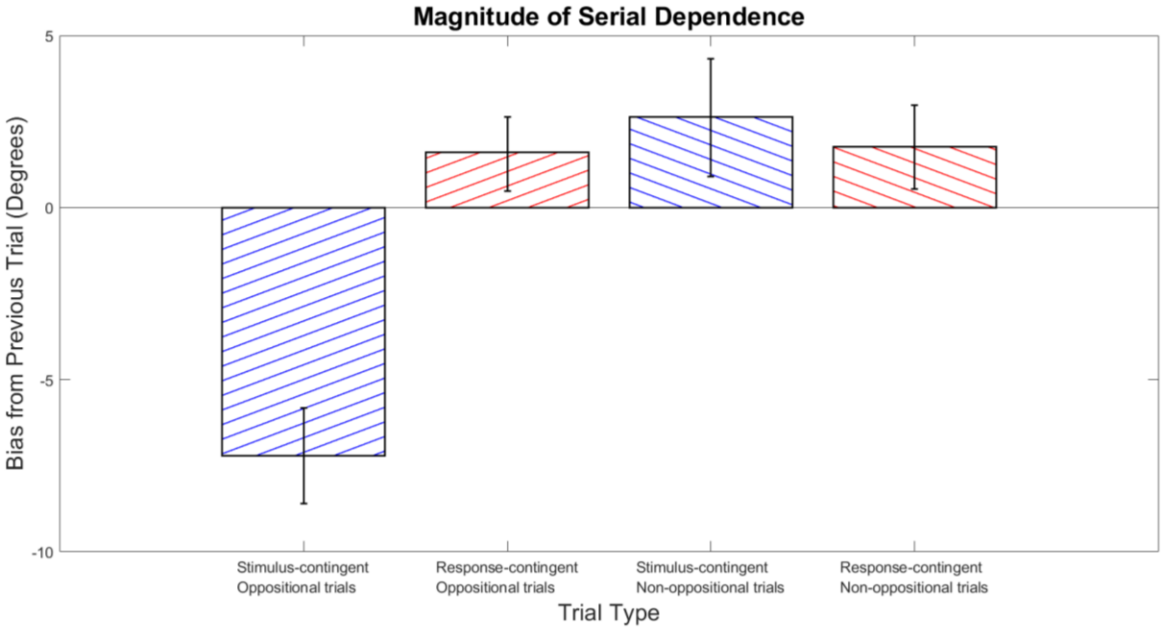

Figure C1. Response- and stimulus-contingent biases for oppositional and non-oppositional trials. Residualisation is only applied to response-contingent analysis for oppositional-trials. Response-contingent non-oppositional trials were subjected to residualisation.