Task feedback suggests a post-perceptual locus of serial dependence

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Abstract

Decisions across a range of perceptual tasks are known to be biased toward stimuli and choices from the past. So-called serial dependence is thought to be an adaptive low-level mechanism that promotes perceptual stability across visual inputs. However, recent studies suggest post-perceptual mechanisms may instead contribute to serially-biased responses, calling into question the locus of serial dependence and the nature of integration of past and present sensory inputs. Here, we uncover decisional contributions to serial dependence that account for the majority, if not all of the bias. We measured serial dependence in a 3D motion extrapolation task where uncertainty in the sensory information varied from trial to trial. Furthermore, visual and auditory response feedback were provided to a subset of participants on every trial. We found that responses were significantly more biased toward the previously reported motion direction rather than the previously presented direction, with larger biases on trials with greater uncertainty in the sensory input. Critically, response feedback was associated with an abolishment of bias toward the previously presented direction, and a significant reduction of bias toward the previously reported direction. These results provide clear evidence for a post-perceptual locus of serial dependence and support the role of serial dependence as a behavioral strategy to overcome sensory uncertainty.

Keywords

Serial dependence; 3D motion perception; sensory uncertainty; feedback

Introduction

Perceptual reports are not uniquely determined by external stimulus properties. They also depend on internal states of the observer, such as attention and prior knowledge. One example that illustrates the contribution of internal state is serial dependence: the finding that recent stimulus history can bias current perceptual reports (Fründ et al., 2014; Fischer & Whitney, 2014). Serial dependence is thought to be adaptive. Because most features in the environment are stable, especially over short time scales, the brain may incorporate recent information into current estimates as a means of reducing noise in instantaneous sensory signals.

Since its initial discovery, numerous papers have observed serial dependencies across a range of high- and low-level perceptual dimensions, task structures, and sensory modalities (Burr & Cicchini, 2014; Fischer & Whitney, 2014; Liberman et al., 2014; Xia et al., 2016; Alais et al., 2017; Bliss et al., 2017; Cicchini et al., 2017; Kiyonaga et al., 2017; van Bergen & Jehee, 2017; Clifford et al., 2018; Fornaciai & Park, 2018; Liberman et al., 2018; Alexi et al., 2018; Manassi et al., 2018; Suárez-Pinilla et al., 2018; Fritsche & de Lange, 2019; Van der Burg et al., 2019; Pascucci et al., 2019; Samaha et al., 2019; Barbosa & Compte, 2020; Kim et al., 2020; de Azevedo Neto & Bartels, 2021; Ceylan et al., 2021; Kim & Alais, 2021; Pascucci & Plomp, 2021; Manassi & Whitney, 2022). An unresolved question from this line of work is whether serial dependence manifests in perceptual or decision-making processes (or both).

It is clear that serial dependence is not simply due to hysteresis in motor processes. The effect does not depend on the need for a motor response (Fisher & Whitney, 2014; Cicchini et al., 2018; Manassi et al.2018; Fornaciai & Park, 2018). However, the effects of task and stimulus characteristics are less clear. Prior work has questioned whether serial dependence in orientation tasks arises in perception since attractive dependencies seem to disappear when a 2AFC appearance-based task is used (Fritsche et al., 2017). On the other hand, when past and previous stimuli were close in orientation, attractive serial dependence was observed in the same 2AFC task (Cicchini et al., 2017), suggesting that serial dependence can manifest in appearance-based tasks.

A post-perceptual locus is suggested based on findings that the magnitude of serial dependence increases as a stimulus is held in working memory (Fritsche et al., 2017; Bliss et al., 2017), and disappears altogether when a previous stimulus is encoded but not reported

(Bae & Luck, 2020). Further work supporting a role of post-perceptual processes found that attractive serial dependence is observed between stimuli that share no overlap in low-level features, but which require the same type of response (Ceylan et al., 2021).

One way of gaining insight into the perceptual or decision-making locus of biases in psychophysical tasks is to assess whether trial-by-trial feedback regarding the accuracy of reports minimizes serial dependence bias. Perceptual biases are thought to be robust to feedback - simply telling someone that their report is incorrect typically does not correct the way illusions appear (Firestone & Scholl, 2014). However, prior work on serial dependence has seldom used trial-by-trial feedback.

A second open question regarding serial dependence is the computational principle that determines when and how information about previous and current inputs gets combined. Although there are several distinct accounts of serial dependence, many share the notion that prior and current inputs are weighted proportional to the uncertainty with which they are internally represented (Cicchini et al., 2014; Fischer & Whitney, 2014; Cicchini et al., 2018; van Bergen & Jehee, 2019; Samaha et al., 2019; Kim & Alais, 2021) and that integration is strongest when past and present inputs are similar (Fritsche, 2016; Cicchini et al., 2018; Fritsche & de Lange, 2019; Lidström, 2019). Although there is evidence for both of these principles (Cicchini et al., 2018), recent work suggests that uncertainty-weighting is not a general principle in that the uncertainty associated with only the current, but not the previous trial, is incorporated (Ceylan et al., 2021; Gallagher & Benton, 2022).

Our aim here was twofold. First we investigated the role of task feedback to gain insight into the perceptual or decision-making locus of serial dependence. Second, we evaluated the role of perceptual uncertainty of both current and previous stimuli to gain insight into the computational principle underlying serial dependence.

We used a 3D motion task to leverage perceptual uncertainty associated with 3D motion perception (Cooper, van Ginkel, & Rokers, 2016). In this paradigm, task feedback can significantly improve performance (Fulvio & Rokers, 2017). Moreover, perceptual uncertainty varies systematically across 3D motion directions (Fulvio & Rokers, 2017; Rokers et al., 2018) allowing us to evaluate sensory uncertainty associated with both prior and current sensory

inputs. Our results indicate that the majority of serial dependence occurs post-perceptually and that uncertainty-weighting is applied unevenly - more so for the current than for previous inputs.

Results

Current reports are biased toward previous reports

To address the perceptual and post-perceptual contributions to serial dependence and the principles governing integration of past and present inputs, we analyzed data from a 3D motion perception task (**Fig. 1**). On each trial, a target with one of three contrast levels (“low”, “mid”, “high”) traversed a trajectory of random direction in 360° for one second before disappearing. Participants adjusted the position of a rectangular cube (“paddle”) along a distant invisible orbit that circled the display to the location that would intercept the target had it continued along the trajectory. One group of participants (n=37) did not receive feedback about their performance at any point during the experiment, whereas a second group of participants (n=24) received visual and auditory feedback about their performance at the end of each trial.

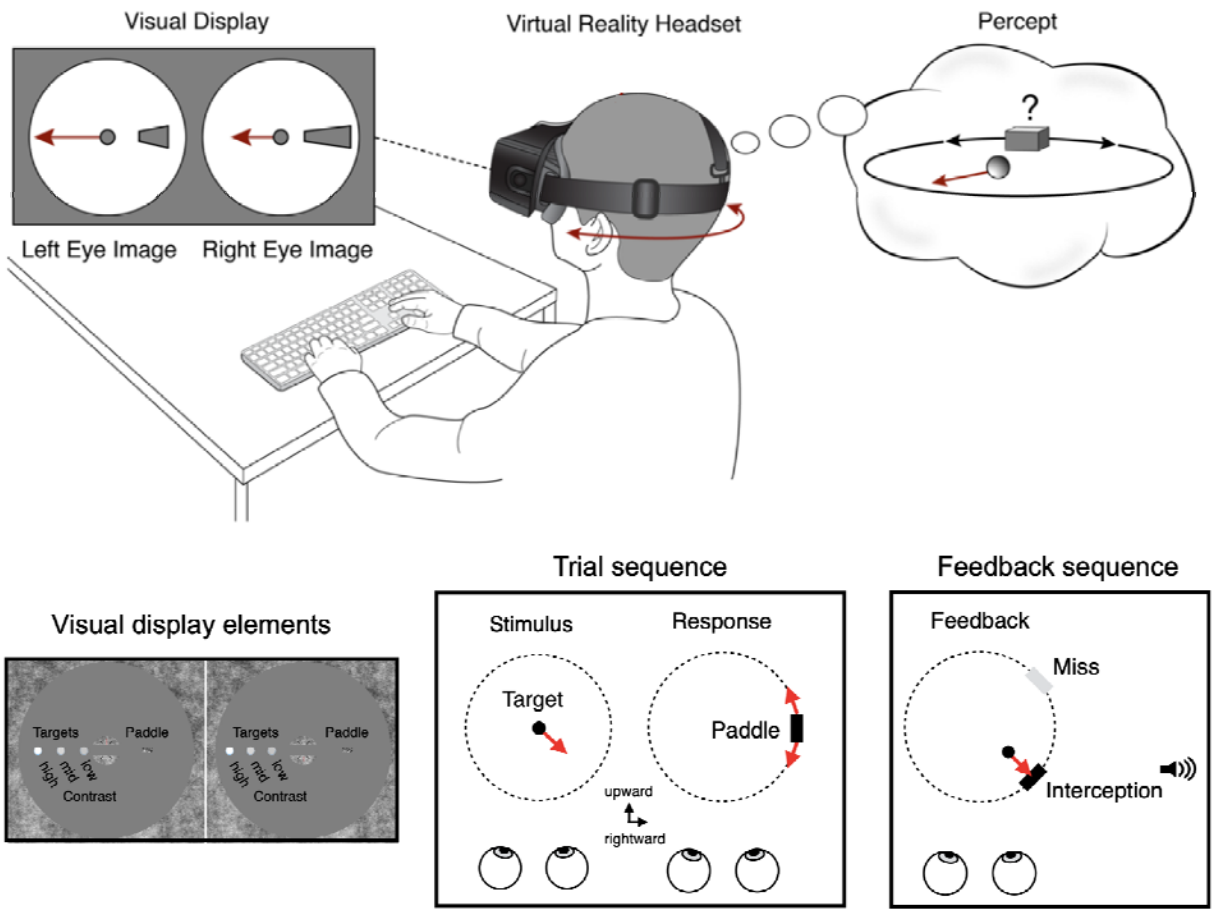

Fig. 1. **Experimental paradigm.** Upper panel: Participants viewed a 3D scene inside a virtual reality headset that consisted of a 1/f noise-mapped planar surface ("wall") with a circular aperture. Lower panel: A small fixation patch with superimposed nonius lines resided in the center of the aperture. The trial sequence consisted of a white circular target of variable contrast ('low', 'mid', or 'high') appearing at fixation and traversing a random trajectory along the x (lateral) and z (depth) planes for 1 second before disappearing. (Note that for display purposes, the targets are shown separately at eccentricity in the "Visual display elements" panel.) When the target disappeared, participants adjusted the position of a 3D rectangular block ("paddle") to the location along an invisible orbit (drawn as a dashed circle here for display purposes) that would intercept the target had it continued along its trajectory. One group of participants did not receive feedback and pressed a key to begin the next trial with a new target. A second group of participants received visual and auditory feedback on every trial. The feedback sequence comprised the target reappearing at its last visible location and continuing along its trajectory to the invisible orbit. An interception occurred when the target reached the paddle; otherwise, the setting resulted in a miss. An auditory signal corresponding to a "hit" sounded upon interception, otherwise, a "miss" sound was played.

We first computed serial dependence in the 3D motion perception task in the absence of task feedback. Consistent with previous studies, current reports were biased toward the previous trial's *presented* direction (serial dependence amplitude, a = 2.56°, 95% CI: [1.39°, 3.87°], p < .001) ; **Fig. 2a**). Current reports were also biased toward the previous trial's *reported* direction (a = 9.57°, 95% CI: [6.97°, 12.46°], p < .001 ; **Fig. 2a**). Critically, the bias toward the *reported* direction was greater than that toward the previous trial's *presented* direction (□a = 7.01, 95% CI: [4.3812°, 10.1206°], p < .001). Whereas the bias toward previous stimuli was, on average, around a few degrees, consistent with prior work using motion and orientation stimuli (Alias et al., 2017; Fritsche & de Lange, 2019; Samaha et al., 2019; Kim et al., 2020; Celyan et al., 2021; but see Fischer & Whitney, 2014 who reported biases >8° in several conditions), the bias toward previous reports was ~9.6 deg, nearly 4 times larger than that towards previous stimuli, suggesting a much stronger reliance of report.

This result indicates that the serial dependence was based on the *reported*, rather than the *presented*, motion direction (see also Ceylan et al., 2021). Depth confusions, where approaching stimuli are reported as receding (or receding stimuli as approaching) are relatively common in this 3D motion perception task (Fulvio & Rokers, 2017). Thus, the presented and reported motion direction can be strongly dissociated in this task, allowing us to isolate the contributions of visual input and perceptual report on serial dependence. We repeated the above analysis but now only considered the high-error motion-in-depth misreport trials omitted from the preceding analysis. We found a significant attractive bias toward the previous trial's *reported* direction (a = 9.01°, 95% CI: [5.30°, 11.46°], p < .001; **Fig. 2b**). However the bias now appeared as repulsive when considering the previous trial's *presented* direction (a = -5.17°, 95% CI: [-7.02°, -3.45°], p < .001; **Fig. 2b**). These results suggest that recent decisions and/or actions account for the serial dependence in this task. To understand the post-perceptual contributions to serial dependence, we next analyzed the impact of task feedback.

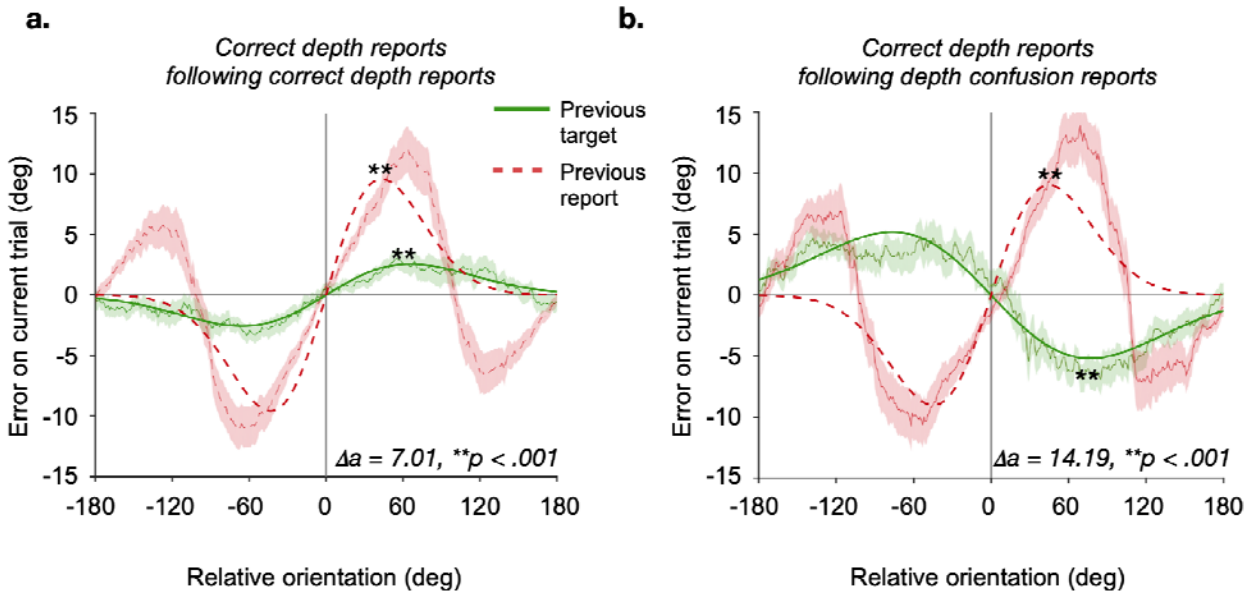

Fig. 2. **Serial dependence is driven by previous reports when no feedback is provided. (a.)** Serial dependence curves and DoG fits to errors on correct depth report trials following correct depth report trials, sorted according to the previous trial's target direction (green) and the previous trial's report (red). **(b.)** Same as **(a.)** except the curves and fits are to errors on correct depth report trials following depth confusion trials. Shaded bands represent +/-1 SEM. **corresponds to bootstrapped *p*-values < .001; □*a* refers to the difference in amplitude parameter between trial sortings.

Task feedback greatly reduces serial dependence

The significant serial bias reported above extends the finding of serial dependence to the 3D motion domain. However, the greater dependence on previous trial *reported* target direction rather than previous trial presented direction challenges the notion that serial dependence arises solely from low-level sensory processes. We have shown previously that report feedback reduces depth confusions and improves overall performance (i.e., percentage of interceptions) in this experiment. Rapid learning occurs early in the first block of training followed by a much slower improvement over time (Fulvio & Rokers, 2017). Because the performance improvements occur much more rapidly than would be expected based on perceptual learning, we believe the performance improvements are due to the appropriate evaluation of the available visual cues in the stimulus display rather than changes in low level sensory processing *per se*.

We therefore tested the interpretation that serial dependence in 3D motion judgments arise from post-perceptual processes by assessing serial dependence in the performance of participants who received visual and auditory task feedback on every trial.

When considering the *presented* motion direction, task feedback eliminated any attractive serial dependence (a = 0.81°, 95% CI: [-0.39°, 1.45°], p = .23; **Fig. 3a, Supplementary Fig. S1**). Thus, while participants in the no feedback condition exhibited significant serial dependence based on the presented motion direction (a = 2.56°, 95% CI: [1.39°, 3.87°], p < .001), this effect disappeared for participants that received trial-to-trial feedback (no-feedback versus feedback: Δa = 1.75°, 95% CI: [0.38°, 3.40°], p = .012; **Fig. 3a**).

When considering the previously *reported* motion direction, task feedback strongly reduced the attractive bias (Δa = 7.96°, 95% CI: [5.23°, 11.02°], p < .001; **Fig. 3, Supplementary Fig. S1**), although it remained significant (a = 1.62°, 95% CI: [0.66°, 3.11°], p = .0013; **Fig. 3b**). The reduction in the feedback group was also confirmed with our model-free measure of serial bias (Welch two-sample $t(47.84) = 2.504$, p = .016; **Fig. 3c**).

These findings further support the idea that participants rely on their recent decisions and/or actions in their current reports in the context of this 3D motion task. In particular, the fact that feedback seemed to abolish serial attraction towards the previous stimuli but preserved some small attractive bias towards the previous reports is surprising. In the feedback group, participants were presented with the target motion direction again during the feedback stage and were thus provided with an opportunity to update their estimate of the motion direction on that trial, yet this did not eliminate the dependence on the previous report. In other words, participants who saw the presented motion again during the feedback portion of the trial, were still systematically biased toward their report rather than the now more recently re-presented direction.

Thus, in what follows, we will focus on serial dependence with respect to *reported* rather than *presented* direction. We do, however, report analyses based on the previous trial's presented direction in Supplementary Materials (**"S1-presented direction analysis"**). Furthermore, in keeping with previous practice, we omitted high error trials (i.e., depth confusion trials) from our analyses to make the effects easier to contextualize. However, we do provide the results of the

main analyses with all trials included in Supplementary Materials as well ("**S2-all trial analysis**").

Investigating how serial dependence changes across the three experimental blocks, we found that dependence on reported direction was already significantly reduced compared to reports without feedback by the end of the first block (□*a* = 7.67°, 95% CI: [3.88°, 10.93°], $p < .001$) and continued to decline with additional trial-to-trial feedback (**Fig. 3d**). Using a model-free quantification, serial dependence was undetectable in blocks 2 and 3 with feedback (mean bias (block 2) = 0.45°, CI = [-2.37°, 3.27°], $t(23) = 0.332$, $p = 0.74$; mean bias (block 3) = 1.32°, CI = [-0.17°, 2.80°], $t(23) = 1.834$, $p = 0.08$). Similar results were also observed when comparing serial dependence across blocks with respect to previous target direction (**Supplementary Materials Fig. S1-1**) and when using all trials in the analysis (**Supplementary Materials Fig. S2-1)**.

Because our study design included additional manipulations, some of which were not relevant to the current analyses, we fit a linear mixed effects model to the model-free serial bias data that accounts for all manipulations, with (i) feedback (2 levels: with & without), (ii) current trial target contrast (3 levels: low, mid, & high), (iii) head-tracking condition (3 levels: fixed, active, & lagged), and (iv) block order as predictors. The resulting fit indicated significant main effects of feedback ($F(1,542) = 14.669$, $p < 0.001$) and current trial target contrast ($F(1,542) = 27.47$, $p < .001$) only. Head-tracking condition and block did not play a significant role in serial bias, and we did not find a block by feedback interaction. It is worth noting that because there was variability in the effect of block due to the differential effects of head-tracking conditions on performance overall (see Fulvio & Rokers, 2017), specific effects of these factors are likely under-powered and obscured in this data set. A more targeted investigation of block order x feedback effects may be of interest for future research. We next turn to factors that directly impact sensory uncertainty, including target contrast.

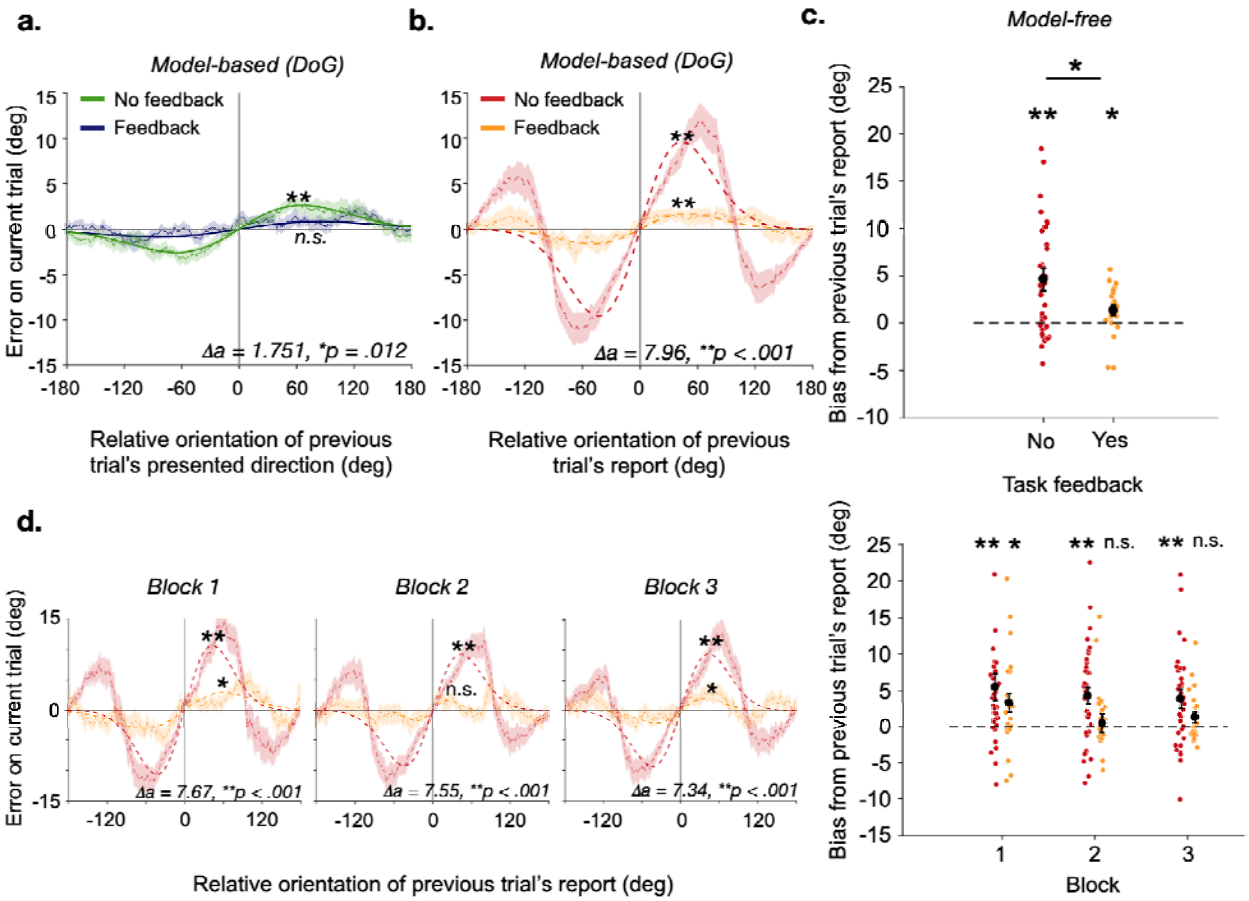

Fig. 3. Task feedback reduces serial dependence. (a.) Serial dependence curves and DoG fits to data sorted according to the previous trial's target direction when feedback was not provided (green) and when visual and auditory feedback were provided (blue). **(b.)** Serial dependence curves and DoG fits to data sorted according to the previous trial's report when feedback was not provided (red) and when visual and auditory feedback were provided (orange). **(c.)** Model-free serial bias with respect to the previous trial's report for the two feedback conditions. Circular symbols correspond to individual subject biases; black symbols correspond to group means. **(d.)** Same as **(b.)** & **(c.)** except the curves, fits, and model-free serial bias are computed with respect to data split out by experimental blocks. Shaded bands and error bars represent +/-1 SEM. **corresponds to *p*-values < .01; *corresponds to *p*-values < .05; n.s. non-significant; Δ*a* refers to the difference in amplitude parameter between trial sortings with and without feedback.

Current trial sensory uncertainty increases serial dependence

A sensory uncertainty account of serial dependence predicts that greater uncertainty in the estimate of the current target's motion leads to greater reliance on recent experience. And, conversely, that greater uncertainty in the previous trial should lead to a smaller impact of recent experience. Here, we tested both predictions by manipulating the reliability of the sensory information about the target's motion on the current and previous trial through variation in target contrast.

We computed serial dependence on previous reported direction as a function of current trial target contrast (i.e., low, mid, or high) and found that increases in current trial target contrast were associated with reduced serial dependence. These results are in line with a sensory uncertainty based account, particularly for the high contrast level used here (**Fig. 4a**). This pattern held for both feedback groups, but dependencies were significantly smaller (or absent) when feedback was provided (bootstrapped *p*-values < .001 for all three contrast levels). This pattern of results was also observed in dependencies based on previous presented target direction (**Supplementary Fig. S1-2a**). Similar qualitative trends were observed when all trials were included in the analysis (**Supplementary Fig. S2-2a**).

Interestingly, the relationship with the previous trial's target contrast was less straight-forward. A sensory uncertainty based explanation would predict that greater target contrast on the previous trial would be associated with a more reliable estimate on that trial, which should have greater impact on the current trial's estimate. With feedback, reliance on the previous reported direction when the previous trial's target contrast was mid or high was significant but not when the previous trial's target contrast was low (a_{high} = 1.664°, 95% CI: [0.198°, 3.2916°]; a_{mid} = 2.398°, 95% CI: [0.887°, 4.512°]; a_{low} = 1.122°, 95% CI: [-1.486°, 2.733°] **Fig. 4b**). However, in the no-feedback condition, reliance on the previous trial's reported direction was significantly reduced when the previous target contrast was high, compared to when the previous trial's target contrast was mid or low(a_{high} = 7.545°, 95% CI: [5.370°, 10.669°]; a_{mid} = 11.63°, 95% CI: [8.963°, 14.520°]; a_{low} = 10.780°, 95% CI: [7.894°, 13.676°]; **Fig. 4b**). Similar trends were observed when considering reliance on previous target direction for the no-feedback condition; no reliance was observed at any target contrast level with feedback (**Supplementary Fig. S1-2b**). Results for both analyses were similar when all trials were included (**Supplementary Fig. S2-2b**). This pattern of results suggests that the reliability of the current trial's sensory estimate is a stronger

predictor of the degree of dependence than the previous trial's sensory reliability (see also Gallagher & Benton, 2022).

In an additional analysis, we considered the *relative* contrast between the current and the previous trial and found that dependence on the previous trial's reported direction was consistently significant for both feedback groups when the previous trial's target contrast was higher than the current trial's target contrast (**Fig. 4c**), a pattern which did not emerge when performing the same analysis considering dependence on the previous trial's target direction (**Supplementary Fig. S1-2c**) and when performing the analysis with all trials included (**Supplementary Fig. S2-2c**).

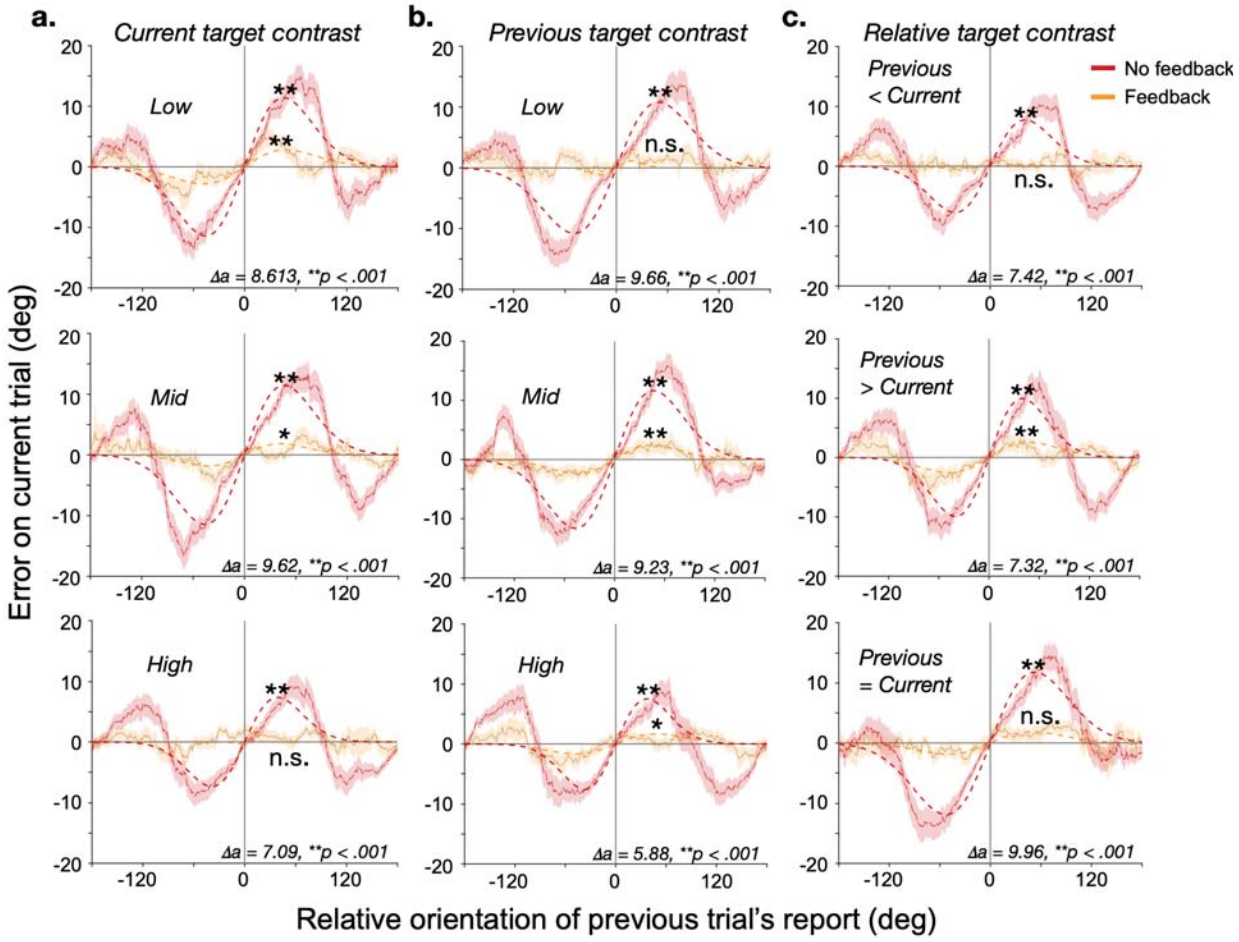

Fig. 4. Serial dependence is modulated by sensory reliability due to target contrast. (a.) Serial dependence curves and DoG fits to data sorted according to the previous trial's report when feedback was not provided (red) and when visual and auditory feedback were provided (orange) on low (top), mid (middle), and high (bottom) target contrast trials. **(b.)** Same as **(a.)** except the curves and DoG fits are computed with respect to data split out by previous trial target contrast. **(c.)** Serial dependence curves and DoG fits to data sorted according to the previous trial's report when the previous trial had lower target contrast than the current (top), higher contrast than the current (middle), and equal contrast to the current (bottom). Shaded bands represent +/-1 SEM. **corresponds to Bootstrapped *p*-values < .01; *corresponds to Bootstrapped *p*-values < .05; n.s. non-significant; □*a* refers to the difference in amplitude parameter between trial sortings with and without feedback.

The results of the target contrast-based analyses therefore support a decision-based post-perceptual strategy (Pascucci et al., 2019; Ceylan et al., 2021) underlying serial dependence whereby decision and/or actions on previous trials are incorporated into the response on the current trial to overcome uncertainty in the perceptual estimate due to reduced quality of the signal (e.g., low target contrast) and a failure to extract the relevant sensory cues in the absence of feedback (Fulvio & Rokers, 2017).

To further investigate if perceptual uncertainty is a driver of serial dependence effects, we considered an additional source of uncertainty in the trial-to-trial estimates of 3D motion direction. Specifically, motion-in-depth signals (i.e., z motion) are less reliable than lateral (x) motion signals (Rokers et al., 2018). Indeed, these differences in reliability can explain depth confusions in 3D motion perception. Thus, a sensory-uncertainty based account predicts that serial dependence impacts estimates of the motion-in-depth component much more substantially than estimates of the lateral motion component. This predicts a pattern of results where, when large response errors are omitted - as is usually done in these kinds of analysis - serial dependence effects should be larger on trials in which the presented direction has a greater motion-in-depth component than on trials in which the presented motion direction has a larger lateral component. To test this prediction, we split trials into two groups: an "approaching/receding" target direction group and a "leftward/rightward" target direction group (see **Fig. 5**). As expected, in the absence of feedback, there is a significantly greater reliance on previous trial reports when the current trial's target direction is primarily approaching or receding (□*a* = 3.66°, 95% CI: [0.74°, 6.23°], *p* = .013). The tendency to rely on previous trial reports when the current trial's target direction is primarily approaching or receding is significantly

reduced with feedback (□*a* = 6.47°, 95% CI: [4.56°, 8.44°], *p* < .001), to a level comparable to the reliance on previous trial's report when the current trial is moving primarily leftward or rightward (□*a* = -0.25°, 95% CI: [-2.00°, 1.55°], *p* = .83). Similar trends were observed when considering reliance on previous target direction (**Supplementary Fig. S1-3**).

We caution however, that omission of trials with large response errors can be counterproductive in understanding serial dependence in terms of uncertainty. In fact, when large response errors are included, an uncertainty-based account predicts that serial dependence should be more apparent on trials in which the presented direction has a greater lateral component than on trials in which the presented motion direction has a larger motion-in-depth component because large response errors will be more broadly distributed for stimuli with large motion-in-depth components. This is indeed what we found (see **Supplementary Fig. S2-3**). In sum, the effects observed in both versions of the analysis (i.e., omitting or including large error trials) confirm that feedback significantly reduces bias and that the bias can be understood in terms of the much greater uncertainty for motion-in-depth in all cases.

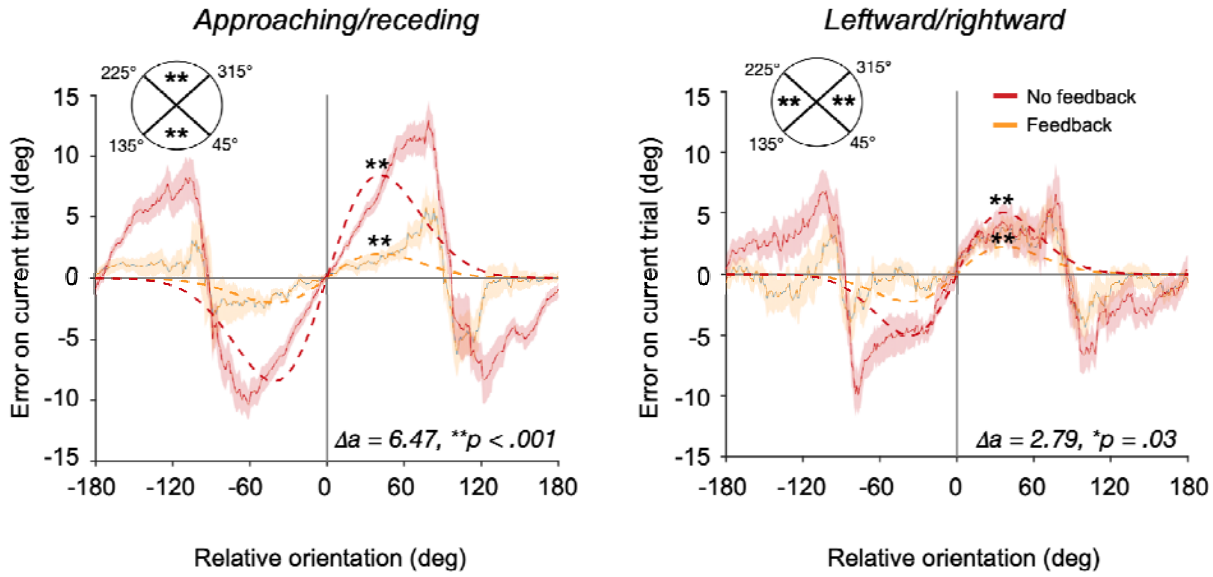

Fig. 5. Serial dependence is modulated by sensory reliability due to target motion-in-depth. Serial dependence curves and DoG fits to data sorted according to the previous trial's report when feedback was not provided (red) and when visual and auditory feedback were provided (orange) on trials in which the target motion was primarily approaching or receding (left) and trials in which the target motion was

primarily leftward or rightward (right). Shaded bands represent +/-1 SEM. **corresponds to Bootstrapped *p*-values < .01; *corresponds to Bootstrapped *p*-values < .05. *a* refers to the difference in amplitude parameter between trial sortings with and without feedback.

Discussion

Serial dependence – the impact of recent stimulus history on current perceptual reports (Fründ et al., 2014; Fischer & Whitney, 2014) – is a pervasive finding in many psychophysical domains. In the current study, we show that serial dependence reflects greater reliance on the previously *reported* direction than the previously *presented* direction. Critically, we showed that serial dependence is not a given - reducing sensory uncertainty and providing explicit feedback about performance on a trial-to-trial basis was associated with attenuation of serial dependence. In particular, we found a near abolishment of serial dependence with task feedback.

These results inform the perceptual and decisional contributions to serial dependence. Earlier accounts posited a "continuity field" that gives rise to serial dependence through a spatiotemporally tuned orientation-selective mechanism that promotes visual stability over time (Fischer & Whitney, 2014; Liberman et al., 2014). Thus, serial dependence could be construed as an adaptive bias that promotes temporal continuity given that many real-world scenarios tend to be stable (Kiyonaga et al., 2017), despite being suboptimal in the laboratory where such real-world priors often do not apply. More recent findings have called into question the perceptual locus of serial dependence, implicating post-perceptual processes as the source (Fritsche et al., 2017; Pascucci et al., 2019; Bae & Luck, 2020; Ceylan et al., 2021).

Here, we leveraged key aspects of a 3D motion judgment task. First, motion stimuli are dynamic, providing challenges for an account of serial dependence as an adaptive strategy under environmental stability. Furthermore, 3D motion perception tasks allow for very large errors, specifically, errors in which the reported target direction can be (and often is) in direct opposition to the presented target direction. Importantly, such errors are not simply random guesses – although participants frequently confuse the motion-in-depth direction (i.e., whether the target was approaching/receding), they rarely confuse the lateral (left/right) component of the target's motion. Furthermore, this phenomenon can be explained by sensory uncertainty in a

Bayesian inference framework (Rokers et al., 2018). Although serial dependence was found for both the previous presented and previous reported target direction, the bias was significantly greater for the reported direction. In particular, for trials following those in which the motion-in-depth was reported in the opposite direction of the target (i.e., approaching or receding), serial dependence was strongly attracted toward the previous reported direction and strongly *repulsed* from the previous presented direction. Further support for a post-perceptual explanation of serial dependence comes from the analysis of performance when participants received trial-to-trial visual and auditory feedback. Feedback was associated with a complete abolishment of serial dependence with respect to the previous *presented* direction and a significantly reduced effect with respect to the previous *reported* direction.

There are multiple proposals for how serial dependence may arise from post-perceptual processes. The bump-reactivation hypothesis (Barbosa et al., 2020; Stein et al., 2020) proposes that serial biases originate in working memory through the reactivation of latent activity-silent patterns of neuronal activity related to the last representation from the previous trial, upon initiation of the current trial. As argued by Ceylan et al. (2021), this model can account for biases with respect to previous task-relevant decisions, in our case, the previous reported 3D motion direction, because the decision is likely to be the last representation held in working memory when a trial ends. However, it is surprising that the reliance on previous trial reports lingered when participants were provided with direct visual feedback at the conclusion of each trial that reflected the presented motion direction. This is especially so, because participants evidently used the feedback to improve their performance over the course of the experiment. One possibility is that the visual signal in the feedback phase was simply not salient enough or encoded fast enough to override the representation of the decision, which was carried over regardless of the outcome on the previous trial. Another possibility is that the feedback signals help to reinforce the reliability of the memory of the report.

A simpler explanation is that participants may have adopted a strategy of merely repeating previous responses when unsure about current stimuli (e.g., Treisman & Williams, 1984) or reports were subject to decisional and/or response hysteresis. However, we find clear trial-to-trial fluctuations in the magnitude of serial dependence due to stimulus characteristics (i.e., target contrast and motion direction) and task feedback, which challenge these explanations. The more recent two-process model proposes decision-weighted decoding of sensory input that results in attraction toward previous reports rather than rote repetition (e.g., Pascucci et al.,

2019; Ceylan et al., 2021). The bias toward previous reports emerges in this model during the decision stage as the result of top-down weighting of the output of low-level sensory channels. A memory trace for read-out weights at the decisional stage is incorporated such that channels that have been recently informative (i.e., consistent with recently observed stimuli) are given more weight. Importantly, the formulation of the two-process model allows for the possibility of the top-down decisional influences directly influencing the *perception* of future stimuli, an effect that would not be expected in rote response repetition. Our results alternatively raise the possibility that serial dependence is subject to strategic control, driven at least in part by error signals from explicit feedback about the accuracy of one's previous actions.

The current results also inform the principles governing the sensory integration of past and present sensory input. The sensory reliability of the current stimulus was a stronger and more consistent predictor of serial dependence than the reliability of the previous stimulus. Whereas increases in current trial target contrast were associated with reductions in serial dependence with respect to reported target direction for both feedback and no feedback groups, the effect of previous trial target contrast was less clear. These results are consistent with other work showing that uncertainty in the current sensory estimate drives serial dependence more than previous trial uncertainty (e.g., Pascucci et al., 2019; Ceylan et al., 2021; Gallagher & Benton, 2022). They can be further accounted for by the Two-process model of serial dependence discussed above, in which the influence of the previous trial, whose variability has been discarded, is inversely weighted by the variability associated with the *current* stimulus (e.g., Pascucci et al., 2019; Ceylan et al. 2021). Previous work has also shown that similarity between successive stimuli matters (Fritsche, 2016; Cicchini et al., 2018; Fritsche & de Lange, 2019; Lidström, 2019). Our results extend this notion by showing that previous trial information is more likely to be integrated if the reliability of previous trial's sensory information was greater than or equal to that of the current trial (Figure 4).

The benefit of feedback-based training is also informative with regard to sensory integration. In previous work, we interpreted improvements in accuracy of 3D motion-in-depth judgments with feedback as the result of the inexperienced participants learning to overcome "flatness" priors developed through extensive real-world use of 2D displays and to compel recruitment of the available depth cues that they were otherwise discounting (Fulvio & Rokers, 2017; Fulvio, Ji et al. 2020). Given that integration of multiple cues enhances reliability of visual perception (Chang et al., 2020; Hillis et al., 2004; Knill & Saunders, 2003; Murphy et al., 2013; Oruc et al., 2013;

Preston et al., 2009; Rideaux & Welchman, 2018; Welchman et al., 2005), increasing the number of cues integrated in estimating the target's motion direction may be one way in which feedback reduces serial dependence. This suggests that serial dependence may be a decision strategy employed specifically when the number or reliability of available sensory signals is low.

Feedback may also play a role in improving participants' understanding of the task structure. Whereas real-world stimuli are often stable over various time scales such that taking information from the recent past into consideration when making current decisions could be adaptive (Fischer & Whitney, 2014; Kiyonaga et al., 2017; Braun et al., 2018), psychophysical stimuli, such as those in the current study, are often independent and (pseudo)randomly presented by design. Serial dependence for unrelated stimuli is clearly suboptimal from an experimental point of view, but until participants are made aware of their mistakes, generalizing from experience provides a way of overcoming uncertainty. Indeed, we showed previously that participants in the no-feedback group exhibited a bias to report high contrast targets as approaching and reduced contrast targets as receding (Fulvio & Rokers, 2017), consistent with a dimmer-is-further-away response heuristic (Cooper & Norcia, 2014). In the current results, we show that serial dependence in the reports of the no-feedback group was significantly greater for motion that was primarily approaching or receding compared to when the target was primarily moving laterally thus supporting serial dependence as a behavioral strategy to overcome sensory uncertainty.

Methods

We provide a description of the experimental design and data collection methods that are relevant to serial dependence effects here. We have described the methods more extensively in a separate study investigating the role of response feedback in the recruitment of visual cues in virtual reality (Fulvio & Rokers, 2017).

Participants

Data from 62 participants were used in the current analysis. All had been recruited from the University of Wisconsin - Madison undergraduate student population and were naive to the purposes of the study. The study was approved by the University of Wisconsin - Madison institutional review board. All participants gave informed consent and received course credit for

their participation. After initial data analysis, data from one participant were excluded from further analysis due to excessive serial bias beyond three standard deviations of the group mean. This resulted in a final set of data from 61 participants (30 females) upon which all results reported in the text are based.

Experimental design

All participants completed three blocks of a 3D motion-in-depth extrapolation task while wearing a virtual reality head-mounted display. We designed the experiment to resemble the classic video game Pong to make the task intuitive to participants. A major difference between our experiments and the classic video game however, is that we used virtual reality to present stimuli in three dimensions (primarily the x-z plane), whereas classic Pong presents stimuli in 2D (the x-y plane). See Supplementary Materials for a video illustrating the stimulus and experimental procedure. 37 participants from the final set of 61 used in the current analyses completed the task without feedback on the accuracy of their reports, whereas 24 participants completed the task with visual and auditory feedback.

Visual stimuli

On each trial, the participant fixated the center of a gray circular aperture (7.5 deg radius) within a 1/f noise-mapped planar surface rendered at a viewing distance of 45 cm. A white spherical target (ball, 0.25 deg radius) appeared at fixation and traveled along a random trajectory in the x-z plane for 1 s before disappearing (see **Figure 1**). The target was rendered under perspective projection, so that both monocular (looming) and binocular (disparity) cues to motion-in-depth were present. During the response phase, a rectangular block (paddle, 0.5 cm × 1 cm × 0.5 cm) textured with 1/f random noise was presented.

Procedure

Participants were asked to report the motion direction of the white circular target. To do so, participants adjusted the position of the paddle so that it would intercept the target. Paddle position was restricted to an invisible circular orbit centered on the fixation point (**Figure 1**). In the no-feedback group, participants locked in their responses and continued to the next trial after a 1 second fixation interval. In the feedback group participants instead saw the ball reappear at its last location and continue along its trajectory until reaching the (invisible) circular orbit. If the paddle had been placed such that the ball was intercepted, a cowbell sound played, otherwise, a “swish” sound played. The next trial then began after the 1 second fixation interval.

Within a block, the target appeared at one of three Weber contrast levels: 0.75 (high), 0.55 (mid), and 0.47 (low), in a random, counterbalanced order. Across blocks, three scene rendering conditions were tested in a random order across participants: (i) 'fixed' in which the scene did not update according to the participant's head motion; (ii) 'active' in which the scene updated according to the participant's head motion; (iii) 'lagged' in which the scene updated according to the participant's head motion, but with a random lag of 50 ms on each trial (no-feedback group) or a random lag on each trial drawn from the uniform distribution [0 500 ms] (feedback group). We note that the three scene rendering conditions were included in the study design to address questions beyond the scope of this investigation and do not materially impact the serial dependence results reported here. Participants in the no-feedback group completed 225 trials per block for a total of 675 trials. Participants in the feedback group completed 120 trials per block for a total of 360 trials.

Serial dependence analysis

Serial dependence was quantified using a pipeline similar to that used by Samaha et al. (2019). For each subject, the response error on each trial was computed as the angular distance between the presented and reported motion trajectory. Following previous serial dependence work (Bliss et al., 2017; Fritsche et al., 2017; Samaha et al., 2019), high-error trials were omitted from analysis. In this task, high-error trials were defined as those in which participants mis-reported the direction of the target's motion in depth (i.e., when participants reported an approaching target as receding and vice versa, henceforth named "depth confusion trials "contrasted with "correct depth trials"). Such depth confusion trials were more prevalent in the no-feedback condition compared to the feedback condition (38.5% vs. 18.7%, respectively, on average across conditions). To confirm that the primary results did not depend on the omission of these trials, we also carried out the analyses with depth confusion trials included and report them where appropriate. To remove any global directional biases for individual participants we subtracted their mean signed error across trials from each trial. On average, these mean signed errors computed across all trials were small . ($M_{no\text{-}feedback}$ = 0.353°, $SD_{no\text{-}feedback}$ = 3.173°; $M_{feedback}$ = 0.165°, $SD_{feedback}$ = 3.391°).

Model-based serial dependence was then quantified in two ways. The first way adopted the standard approach of sorting each participant's demeaned errors according to the angular difference between the *presented* target direction on the current and previous trials. The first

trial was omitted because it did not have a previous trial. When trials were removed due to response confusions as described above, the most immediately preceding non-confusion trial served as the previous trial. This approach is reasonable given recent work showing that serial dependence may extend to at least three trials back (Fischer & Whitney, 2014). Nevertheless, to verify that the standard approach did not bias our results, we verified that the effect sizes were similar when trials with response confusions were included - for the no feedback group in which the response confusions were prevalent, the amplitude of the model fit (see text below for model fitting details) to the demeaned errors with respect to the previous trial's presented target direction was *a* = 2.56° with response confusion trials omitted whereas *a* = 0.203° with response confusions included. Although this result might suggest that any serial dependence effects in our data hinge on the omission of confusion trials in our analysis, we repeated the comparison for model fits to the demeaned errors with respect to the previous trial's *reported* target direction, which forms the basis of the majority of the analyses reported below (see **Results** for more information), we found that *a* = 9.57° with response confusion trials omitted whereas *a* = 13.473° with response confusions included. Thus, if anything, the omission of the response confusion trials in our main analyses presented below underestimates the serial dependence in participants' responses. For completeness, we provide the results of the analyses incorporating all trials in Supplementary Materials.

The sorted errors for each participant were then smoothed by a 45-degree wide median filter in 1 degree increments. We then averaged the smoothed data within each group and fitted the averages of each group with a derivative-of-Gaussian (DoG) function of the following form:

$$y = xawce^{-(wx)^2}$$

where *x* is the relative orientation of the target or response of the previous trial, *a* is the amplitude of the peaks of the curve, *w* is the width of the curve, and *c* is a constant √2/e^(-0.5), which scales the amplitude parameter to numerically match the height of the curve in degrees. Fitting was achieved by minimizing the sum of squared errors using the *lsqcurvefit* MATLAB routine, with amplitude *a* and width *w* parameters free to vary between [-15 deg, 15 deg] and [0.001, 0.5], respectively. Note that for the "all trials" analysis (**Supplementary S2**) the

amplitude parameters were free to vary between [-30 deg, 30 deg] to account for the larger range of bias with respect to previous report in the no feedback condition. Statistical significance of the group-level DoG fits was assessed through a bias-corrected and accelerated (BCa) bootstrapping procedure. On each of 100,000 iterations, we sampled subjects with replacement and fit a DoG to the average of the bootstrap sampled data. The value of the amplitude parameter was retained after each iteration, resulting in a distribution of the amplitude parameter of our sample. We also computed the jackknife distribution of amplitude parameters by computing all of the leave-one-sample-out DoG fits. The confidence interval and p-value of the amplitudes of each group fit when compared to zero (i.e., no serial dependence) and when compared to each other were computed using the *BCa_bootstrap* MATLAB function (Van Snellenberg, 2018) which utilized both the bootstrapped and jackknife amplitude distributions.

Model-based serial dependence was quantified in a second way by sorting each participant's demeaned errors according to the angular difference between the presented target direction on the current trial and the *reported* target direction on the previous trial. All other aspects of the analysis were as described above.

Following Samaha et al. (2019), we additionally carried out a model-free analysis to verify that the results were not specific to the model-fitting. For each participant, we computed the median (signed) error across trials where the relative difference between the current and previous stimulus fell within the interval (0 deg, 180 deg), and subtracted that from the median error on trials within the interval (-180 deg, 0 deg). Thus, positive and negative values indicate an attractive or repulsive bias, respectively. Statistical testing was performed using two-tailed t tests, or a linear mixed effects model as described in the main text.

Both model-based and model-free analyses were carried out multiple times on trial sortings according to several questions addressed below. For the basic comparisons between serial dependence on previous target direction and previous report, and between performance with and without feedback, trials across all three blocks were used. For block-based comparisons, serial dependence was estimated separately for each of the three blocks. For target contrast-based comparisons, serial dependence was estimated for each of the three target contrast levels, combining trials across blocks. Finally, for target motion-in-depth direction-based comparisons, serial dependence was estimated for two categories of motion-in-depth direction, combining trials across blocks: (i) "mostly approaching/receding" motion, with trajectory

directions in the following ranges: [45°-135°, 225°-315°]; (ii) “mostly leftward/rightward” motion, with trajectory directions in the following ranges: [0°-45°, 135°-225°, 315°-360°].

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