Rapid adaptive precision weighting in visual perception

William Turner[1*], Oh-Sang Kwon[2], Minwoo JB Kim[2], Hinze Hogendoorn[1,3]

[1]Queensland University of Technology
[2]Ulsan National Institute of Science and Technology
[3]The University of Melbourne

*Corresponding Author
William Turner
williamfrancisturner@gmail.com

Acknowledgements: This work was supported by a QUT ECRIS Grant awarded to WT and an Australian Research Council Grant FT200100246 awarded to HH.

Author Contributions: All authors contributed to conception and design. W.T. developed and ran the simulations. O.K. and M.K. reviewed the code. W.T. drafted the article and all authors reviewed the manuscript.

Competing interests: The authors declare no competing interests.

Abstract

A striking perceptual phenomenon has recently been described wherein people report seeing abrupt jumps in the location of a smoothly moving object ('position resets'). Here, we show that this phenomenon can be understood within the framework of recursive Bayesian estimation as arising from transient gain changes, temporarily prioritising sensory input over predictive beliefs. From this perspective, position resets reveal a capacity for rapid adaptive precision weighting in human visual perception, and offer a possible testbed within which to study the timing and flexibility of sensory gain control.

1. Introduction

Accurate visual localisation of objects is critical for adaptive behaviour, both evolutionarily (e.g., targeting prey while hunting) and in modern life (e.g., navigating through traffic). However, there are instances where localisation goes awry. One of the most striking examples is the 'double drift' illusion, which occurs when a moving object contains internal motion in a direction orthogonal to its global trajectory (see Figure 1A; Lisi & Cavanagh, 2015). Under such conditions, if the object is viewed peripherally, extreme mis-localisations can occur.

Recently, it has been shown that the double drift illusion can be reset, such that people report seeing the object abruptly jump back toward its true position (Nakayama & Holcombe, 2020). These 'position resets' can be triggered by visual transients near the object and/or may occur spontaneously ('t Hart, Henriques, & Cavanagh, 2022). When asked to draw the (linearly moving) object's trajectory, participants draw a zig-zag shaped path (see Fig 1B).

Currently, the cause of position resets is unknown. One high-level account suggests that shifts of attention may somehow reset the perceived position of the object back to its veridical position (Nakayama & Holcombe, 2020). However, a computationally-rigorous account of this phenomenon is lacking, and the question of *why* attention might drive resets has not been addressed.

Here, we consider this phenomenon from the perspective of recursive Bayesian estimation, where perception is viewed as an unfolding inference process in which sensory inputs are combined with internally generated predictions, to derive more precise estimates of world states (e.g., an object's position and speed). From this perspective, we show that position resets can arise from transient gain changes which temporarily prioritise sensory input over predictive beliefs.

2. Model and Results

We simulated an object-tracking model previously used to account for a variant of the double drift illusion (the "curveball illusion"; for full model details see linked code and Kwon et al., 2015). At its core is a generative model of motion dynamics (i.e. the laws of motion) used to derive predictions about current world states. That is, predictions are made about the current position and velocity of an object given its past state. These are integrated with noisy sensory inputs to derive more precise state estimates. This process takes the form of a Kalman Filter which is optimal under the assumption of gaussian noise (Kalman, 1960).

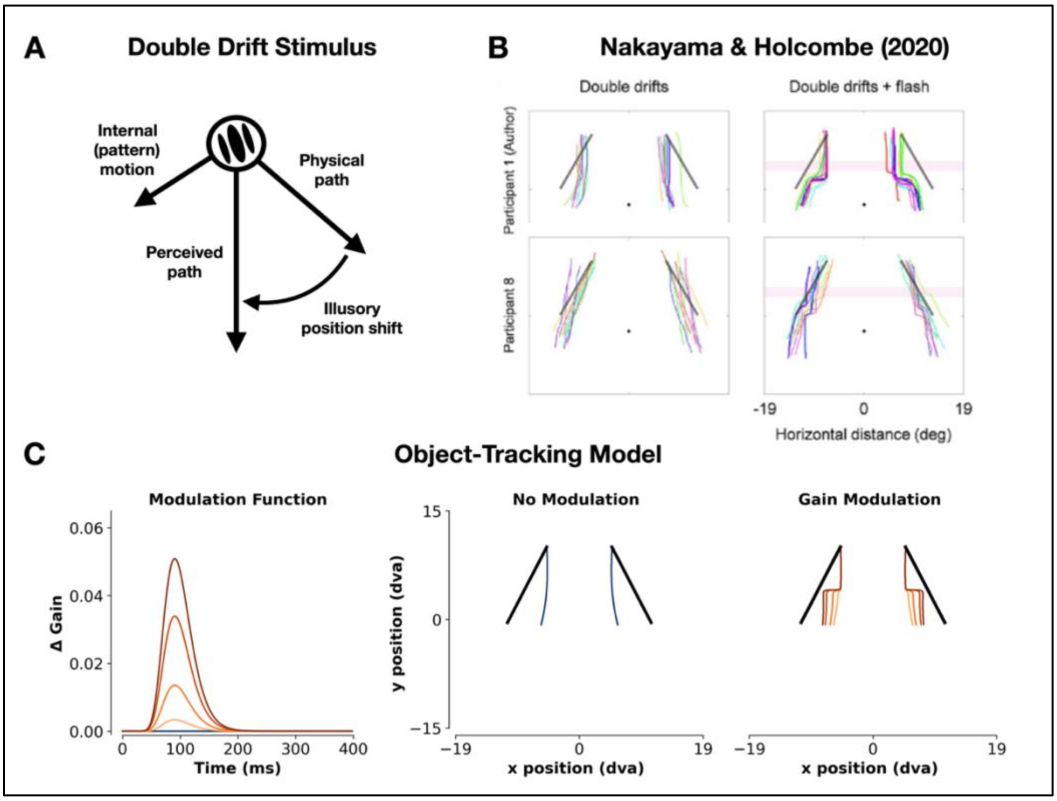

Figure 1. Accounting for 'position resets' in the double-drift illusion. A) When viewed peripherally, a diagonally moving Gabor stimulus can appear to travel along a vertical path if its internal pattern (phase) moves in an orthogonal direction. **B)** With brief flashes near the Gabor, participants report seeing abrupt 'position resets', such that the stimulus appears to move along a zig-zag shaped path. Panels show hand-drawn stimulus trajectories from two participants viewing double-drift stimuli with (right) and without (left) transient flashes (Nakayama & Holcombe, 2020). With flashes, an abrupt kink can be seen midway through the trajectories indicating that participants saw the stimulus jump back toward its true position. **C)** A Bayesian object-tracking model (Kwon et al., 2015) gives a principled account of this effect. Transient gain modulations (modelled via a log-normal function with varying amplitude) drive the rapid re-weighting of inputs and predictions within the model, resulting in a zig-zag shaped trajectory estimate. Black diagonal lines indicate the true stimulus trajectories, blue lines show model

estimated trajectories under no gain modulation, and orange lines show model estimated trajectories under gain modulations of varying amplitude.

In the present simulations, we examined the effect of transient gain modulations on model-derived object trajectory estimates. Here, 'gain' refers to the weight given to incoming sensory information over predictive beliefs in determining the final state estimate. With higher gain, inputs are prioritised over predictions, and vice versa. Within the model, gain is calculated at each time point:

$$K = PH^T(HPH^T + R)^{-1} + M$$

where P is the state covariance matrix, H is the observation matrix, R is the measurement noise covariance matrix, and M is an additive gain modulation matrix. To implement gain modulations, from 900 ms after stimulus onset we varied the diagonal of this matrix according to a log-normal function with varying amplitude (Figure 1C). Simulating modulations of varying strength, we found that transient gain modulations induced position resets. Stronger modulations triggered more abrupt resets, with model trajectory estimates qualitatively mirroring those from Nakayama and Holcombe (2020).

MATLAB and Python code for recreating these simulations is available at: https://github.com/bootstrapbill/position-reset-model.

3. Discussion

We have given a computational account of 'position resets' in visual localisation (Nakayama & Holcombe, 2020). Through the lens of recursive Bayesian estimation, we have shown that resets can arise from gain modulations which temporarily prioritise sensory inputs over predictive beliefs. From this perspective, position resets reveal a capacity for rapid adaptive 'precision weighting' (Yon & Frith, 2021) in human visual perception.

Importantly, the current model is agnostic to the cause of gain changes. At least two hypotheses warrant investigation. First, attention shifts (either bottom-up or top-down) may 'sharpen' incoming sensory information (Nakayama & Holcombe, 2020). With increased precision, these inputs will be upweighted relative to predictions, triggering a reset. Second, abrupt visual transients may trigger a reduction in the precision of internally generated predictions (e.g., 'something has changed, so my predictions may no longer hold'). This too would lead to the prioritisation of inputs over predictions, and thus a reset. (For proof-of-principle simulations of these accounts see linked code.)

These accounts may not be mutually exclusive and could be further tested by examining whether resets are preceded by a sharpening of neural object position representations (Turner et al., 2023; Turner et al., 2024; Yon et al., 2018). As a general test of this perspective, studies could examine whether manipulations which increase sensory uncertainty (visual noise) can cancel out/prevent resets. If this is possible, this would support the core idea that the relative precision of inputs and predictions ultimately determines their perceptual influence. With further support for this account, studies may also investigate the neurochemical basis of gain modulations. For example, by testing whether specific pharmacological interventions can inhibit/disrupt resets (Moran et al., 2013), or by studying pupil-linked arousal dynamics during spontaneous resets (‘t Hart et al., 2022).

If resets reflect rapid precision weighting, then individual variability in this phenomenon should be examined. For example, studies could test whether certain clinical populations are resistant to experiencing resets, as this may be indicative of reduced perceptual flexibility – i.e., a ‘stubborn’ perceptual experience. Relatedly, individual differences in the double drift illusion have been observed to correlate with individual differences in the ‘twinkle goes’ and ‘flash grab’ illusions, suggesting they may share underlying mechanisms (Cottier et al., 2023). Future studies may therefore attempt to account for these illusions within the present framework. As a speculative example, in the twinkle goes illusion an increased reliance on predictions in the face of highly uncertain input (due to dynamic noise) may drive the lingering percept of the stimulus.

In sum, we have shown that ‘position resets’ can arise from transient gain changes, suggesting a capacity for rapid dynamic precision weighting in human visual perception. Future studies may further examine this phenomenon to better understand the temporal dynamics of sensory gain control.

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