Bayesian causal inference drives temporal sensorimotor recalibration

Luigi Acerbi ⟨L.Acerbi@sms.ed.ac.uk⟩, Sethu Vijayakumar ⟨sethu.vijayakumar@ed.ac.uk⟩

Summary. How does the brain evaluate and represent the time interval between a sensorimotor pair of events like a button press and a flash? Psychophysical experiments have shown that the relative position in time of the two events is subject to contraction (causal/intentional binding) [1] and to adaptive shifts which lead to striking time-ordering reversal illusions (temporal recalibration) [2]. The subjective structure and representation of time appears, hence, to be extremely fluid and nonlinear.

In this work, we hypothesize that these phenomena are a consequence of Bayesian causal structural inference [3] and propose a compact generative modelling approach. Specifically, causal binding can be interpreted as an (attractive) prior between potentially related events, while temporal recalibration follows from the inference of the temporal offset between the visual and motor feedback (due to transmission delays, processing times, etc.). In particular, a Bayesian observer should exhibit recalibration to a sensory lag only if two crossmodal sensory events are thought to be causally related – and thus most likely simultaneous; the likelihood of which we propose is driven by a model selection paradigm.

The proposed model obtains excellent fits – as good as the best known empirical fit [2], to psychophysical data of temporal recalibration experiments from different modalities and with various delays between the button press and stimuli. More importantly, having estimated some subject specific parameters (see below), we were able to make predictions about the effect of noisy adaptation stimuli on recalibration with good quantitative match – as expected, temporal recalibration is modulated by stimulus temporal reliability. As a further validation, the sensory parameters obtained by fitting the model to the recalibration data correlated extremely well with those measured in an independent experiment (a time interval discrimination task), implying the model can reliably recover those parameters.

This work presents the first attempts at generative modeling of time interval estimation in a sensorimotor task that goes beyond empirical fitting and provides new ways to investigate departures from the "scalar property" of interval estimation in the subsecond range. This also provides preliminary evidence that several recalibration and fast adaptation phenomenon in the temporal domain can be explained as a consequence of optimal Bayesian structural inference that our brain may be inferring about.

[1] Haggard, P., Clark, S. and Kalogeras, J. "Voluntary action and conscious awareness". *Nature Neuroscience* 5, 382-385 (2002).

[2] Heron, J., Hanson, J.V.M. and Whitaker, D. "Effect before Cause: Supramodal Recalibration of Sensorimotor Timing". *PLoS One* 4 (2009).

[3] Sato, Y., Toyoizumi, T. and Aihara, K. "Bayesian inference explains perception of unity and ventriloquism aftereffect: Identification of common sources of audiovisual stimuli". *Neural computation* 19, 3335-3355 (2007).

Supplementary material. The analytical, MAP solution to the model gives us the recalibration curve (the point of subjective simultaneity, PSS) for a specified adaptation delay d:

$$PSS\left(d;\sigma_0,c,\rho,\eta\right)=\frac{\rho^2}{\sigma^2(d)+\rho^2}\int_{-z^*}^{z^*}dz\,zN\left(z;d,\sigma^2(d)\right)\qquad\text{with } N(x;\mu,\sigma^2)\equiv\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

where $z^*\equiv\sqrt{2\eta(\sigma^2(d)+\rho^2)}$ and $\sigma^2(d)\equiv\sigma_0^2+c^2d^2$. The four parameters are: σ_0 (the bare sensory temporal reliability), c (the coefficient of variation of the scalar property), ρ (the recalibration allowance), η (the *propensity*, *i.e.* an effective prior on causality). For each subject σ_0 and c have been measured with a temporal order judgement experiment. Then ρ and η have been measured in some recalibration condition and the overall model tested in other independent conditions (*e.g.* manipulating σ_0).