Bayesian causal inference drives temporal sensorimotor recalibration

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Introduction

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

Sensorimotor temporal recalibration is the shift of the *point of subjective simultaneity* between an action (*e.g.* a button press) and a sensation (*e.g.* a flash) after repeated exposure to a fixed lag between the two.

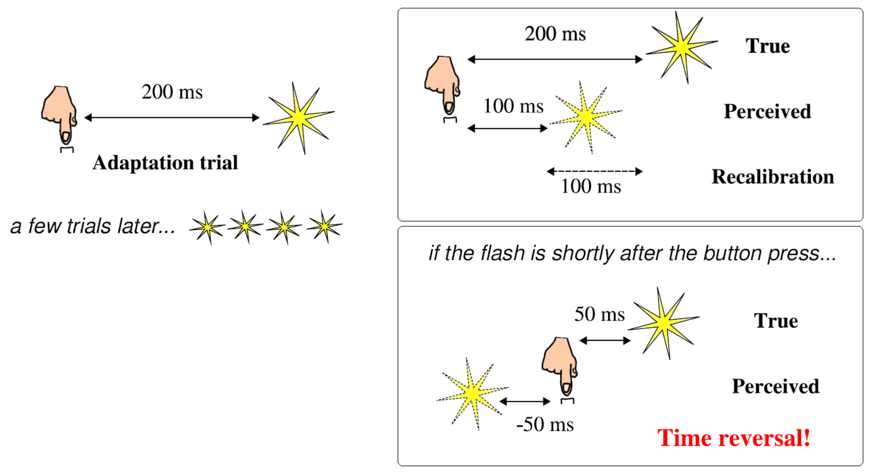

Figure 1: A temporal order illusion induced by temporal recalibration.

- Temporal recalibration works for any motor-sensory pair (visuo-motor, audio-motor, tactile-motor) in almost identical ways, and it transfers across modalities.
- A 'universal' empirical law was proposed [3] that links recalibration to the adaptation delay d

$$PSS(d) = k \cdot e^{-\frac{d}{k'}} \qquad (1)$$

with k, k' two arbitrary parameters that depend on the experimental conditions.

- The empirical law obtains excellent fits of psychophysical data, but it lacks a deeper explanatory or predictive power.

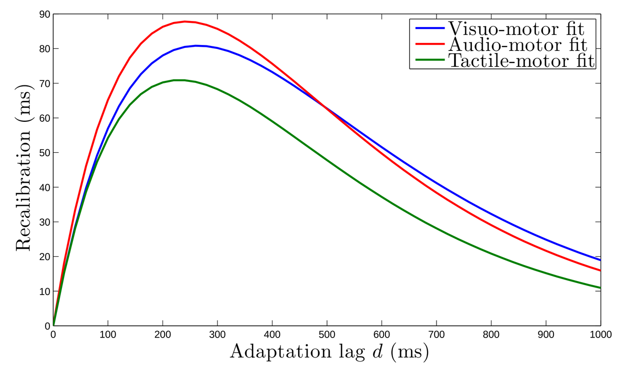

Figure 2: Temporal recalibration curves for various sensorimotor modalities (from [3]).

The above and other results support the main hypothesis that temporal recalibration is caused by an adaptive 'resynchronization' of apparently mismatching sensory and motor streams.

How should the brain recalibrate mismatching sensory and motor streams?
Without any external 'calibrating signal', the brain can only exploit the known structure of the sensorimotor world. For instance, causally related events are usually simultaneous (and contiguous in space, see [4]). So recalibration requires the brain to infer the causal structure of events.

Thesis: Sensorimotor temporal recalibration is driven by Bayesian causal inference.

The Bayesian model

We assume the brain has a generative probabilistic model for the temporal relationship of any action-stimulus pair of events (a trial). For each trial the brain formulates two competing hypotheses regarding the causal relationship C between the two events, which can be either unrelated ($C = 0$) or causally connected ($C = 1$).

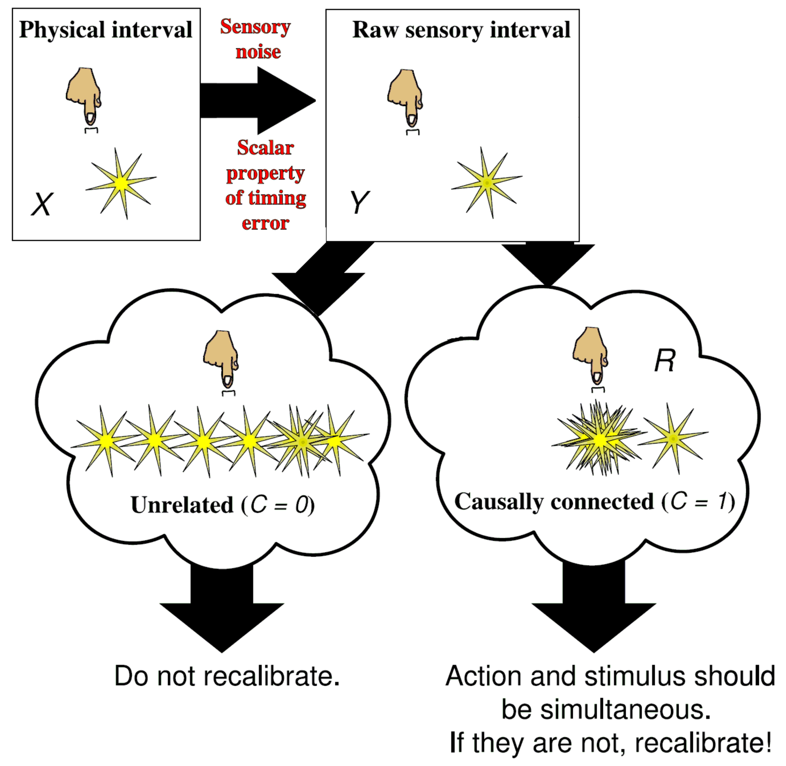

Figure 3: Causal inference and model selection.

The variables in the model are:

- a binary causality variable $C \in \{0, 1\}$;
- the physical time interval X between the two events;
- the offset R between motor and sensory streams;
- the sensed temporal interval Y.

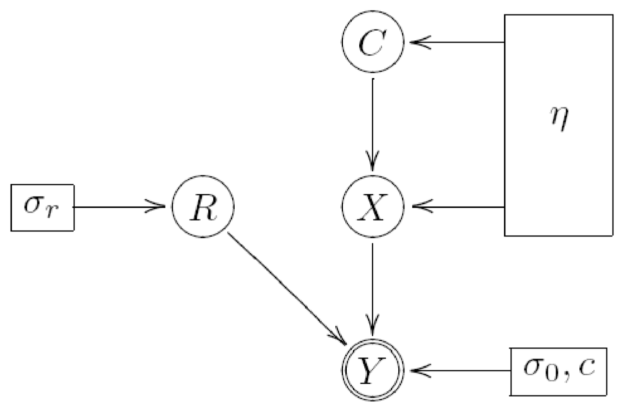

Figure 4: Probabilistic graphical model representing each trial. The four free parameters of the model are in the boxes.

The generative model assumption are that

- if $C = 0$, then $X = 0$ (the two events are simultaneous);
- if $C = 1$, then X takes the form of a uniform distribution (the two events are unrelated).

The relative likelihood of the two causal hypotheses is governed by the single parameter η, called the propensity.
The sensed temporal interval is calculated as

$$Y = X - R + \sqrt{\sigma_0^2 + c^2 d^2} \cdot n$$

where n is a normally distributed random variable, σ_0 is the bare sensory variability, c is the coefficient of variation and d is the adaptation interval (the error follows the *scalar property* of time interval estimation). At last, it is assumed that R follows a Gaussian distribution centered in zero with variance σ_r^2 (simulating a natural limit on recalibration).

Bayesian Inference and Recalibration

Given the sensed temporal interval Y, the brain infers the most likely (MAP) values for X, R and C (Bayesian inference with a model selection component).
The current state of recalibration is then updated from trial to trial according to the inferred values of R. In the limit of infinite trials (*i.e.* a sufficiently long adaptation period) we obtain:

$$PSS\left(d; \sigma_0, c, \sigma_r, \eta\right) = \frac{\sigma_r^2}{\sigma_y^2(d) + \sigma_r^2} \int_{-z^*}^{z^*} dz \, z N\left(z; d, \sigma_y^2(d)\right)$$

with $z^* \equiv \sqrt{2\eta(\sigma_y^2(d) + \sigma_r^2)}$ and $\sigma_y^2(d) = \sigma_0^2 + c^2 d^2$.

Results

Different psychophysical experiments were conducted on the same subjects ($n = 7$) to determine the parameters of the model and test its validity.

TimeStamp: Experiment on visuo-motor time-interval discrimination, used to fix the parameters σ_0 and c of the model.

TimeDrift: The main experiment on visuo-motor temporal recalibration. All subjects performed many sessions with varying adaptation lag d (from 10 ms to 800 ms). The recalibration data were fitted by the model, recovering the remaining two free parameters σ_r and η.

TimeJitter: A novel visuo-motor temporal recalibration experiment in which the adaptation stimuli are noisy in the temporal dimension. All subjects performed different blocks with average adaptation lag $d = 200$ ms and four level of noise $\sigma_d = \{0, 33, 66, 100\}$ ms. Notice that at this point the model has no free parameters.

Consistency of the methods

We performed a 'consistency check' to see if the measured parameters of the subjects are invariant across different experimental layouts. **Figure 5** shows that the results for σ_0 match quite well.

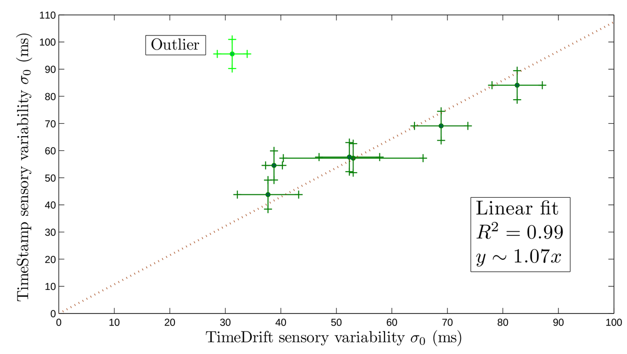

Figure 5: Comparison of σ_0 of all subjects in two different experiments.

Quality of fit

With the same number of free parameters the model performs as well as the universal empirical law (Equation 1) on our and other datasets; see **Figure 6**. $R^2 \approx 0.80$ on our dataset and $R^2 \geq 0.95$ on the datasets from [3].

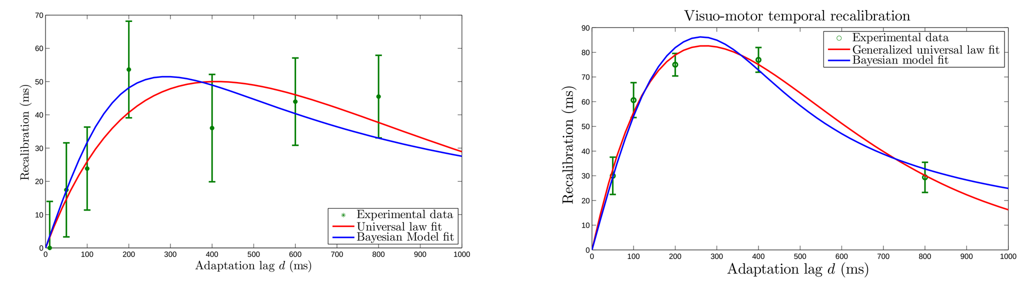

Figure 6: Visuo-motor temporal recalibration. (Left) TimeDrift experiment ($n = 7$). (Right) Dataset from [3] ($n = 5$).

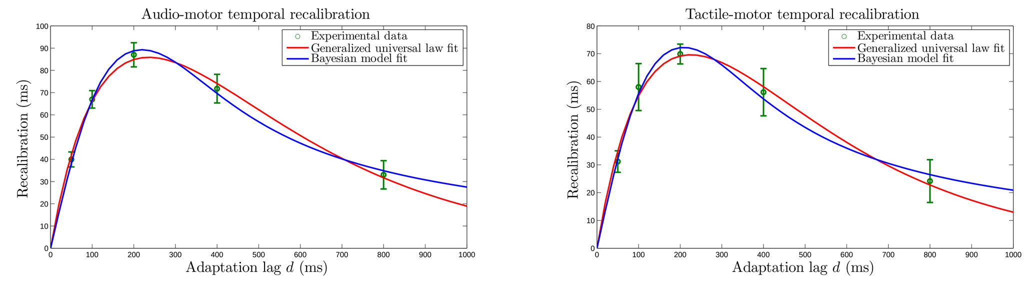

Figure 7: Audio-motor (left) and tactile-motor (right) temporal recalibration. Both datasets are from [3] ($n = 5$).

Recalibration under noisy conditions

We manipulated the temporal variability σ_y by adding some Gaussian noise σ_d in the timing of the adaptation stimuli, so that

$$\sigma_y^2 \longrightarrow \sigma_y^2 + \sigma_d^2.$$

The prediction of the model (**Figure 8**) gives a fair explanation of the observed variance ($R^2 = 0.73$).

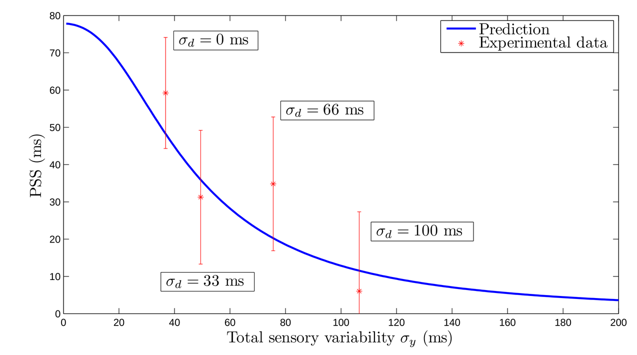

Figure 8: TimeJitter experiment. Prediction of the change in recalibration as a function of the temporal variability σ_y (no free parameters).

Discussion

Features and novel contributions include

- The experimental data show how temporal recalibration is modulated by stimulus temporal reliability.
- The results support the hypothesis that nonlinearity and fast adaptation phenomena in time perception are due to Bayesian inference.
- The control experiments suggest that the modelling choices capture objective properties of the observers.

Further work in the current framework

- The strength of causality can be quantified (the propensity η).
- Investigations of departures from the *scalar property* of time interval estimation.

References

[1] P. Haggard et al, Voluntary action and conscious awareness. *Nature Neuroscience*, 2002.

[2] C. Stetson, et al, Motor-Sensory Recalibration Leads to an Illusory Reversal of Action and Sensation. *Neuron*, 2006.

[3] J. Heron et al, Effect before Cause: Supramodal Recalibration of Sensorimotor Timing. *PLoS One*, 2009.

[4] Sato, Y. et al. Bayesian inference explains perception of unity and ventriloquism aftereffect: Identification of common sources of audiovisual stimuli. *Neural computation*, 2007.

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