Bayesian Causal Inference Underlies Sensory Attenuation in Tactile Perception

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Abstract

Sensory information is attenuated during movement, especially when it is highly predictable. Fuehrer et al. (2022) showed sensory attenuation (SA) of predictable vibrotactile stimuli when performing stroking movements with their finger. We here reconsider these results from the perspective of Bayesian Causal Inference (BCI). Using a generative hidden Markov model (HMM), we simulate SA as a function of inferring external (other-generated) vs. internal (self-generated) causes for sensory signals. We then used optimization to identify individual generative model parameters that best fit observed behavior and obtain a good quantitative fit between detection behavior and our computational model's predictions. In conclusion, our model is well suited for capturing qualitative and quantitative characteristics of task behavior. SA in our model stems from inferring an *internal* cause for externally generated stimuli as a consequence of the participant's probabilistic inference. Our model may guide future efforts to better understand the heterogeneous findings surrounding the phenomenon of SA.

Keywords: Sensory attenuation; Bayesian Causal Inference; tactile perception; prediction

Introduction

Sensory attenuation (SA) in the context of movement has been widely replicated at neural and behavioral levels (Voudouris and Fiehler, 2017). It seems to play a crucial role for agency and movement planning and -execution (Brown et al., 2013). Research suggests that SA is a consequence of precise movement-related sensory predictions (Fuehrer et al., 2022). We model data from the experiment by Fuehrer et al. (2022), where participants were asked to stroke with their index finger over a n object with a textured surface. Before making contact with the object, they received a vibrotactile probe stimulus of varying intensities to the stroking finger. Afterwards, participants had to indicate whether they felt the stimulus or not. The probe's vibration frequency was either congruent or incongruent with the vibratory frequency caused by stroking over the object's surface. The authors found increased attenuation in all movement conditions compared to rest, and stronger attenuation of congruent vs. incongruent probes, suggesting that SA stems from specific predictions. We here adopt the perspective of Bayesian Causal Inference (BCI) and provide a computational model for these findings (Shams and Beierholm, 2022). We view the brain as engaged in causal inference to identify the origin of tactile information. If tactile information is in line with movement-related sensory predictions, it is inferred as self-generated (internal cause) and attenuated. If sensory input violates the movement-related sensory predictions, an external cause for the information is inferred and no attenuation is observed.

Methods

Simulations.

A custom library for Bayesian graphical models was created to implement a hierarchical hidden Markov (HMM) model with $T = 50$ time steps (Fig. **1A**, Endres et al., 2022). Likelihood nodes ($p(f_t|x_t)$) connect tactile predictions to the inferred cause ($x_t \in \{external, internal, none\}$, see Fig. **1B**). Three different stimulus sequences were generated in agreement with the original study: *no probe* (Fig. **1C**), *congruent probe* (where probe frequency is congruent with the frequency felt when stroking the object's surface, Fig. **1G**), and *incongruent probe* (where probe frequency and object frequency do not match, Fig. **1E**).

Model fitting.

To obtain the parameters of participant-specific generative models, we fit the model (Fig. **1A**) to the response data from Fuehrer et al. (2022) using the L-BFGS-B optimizer from the SciPy package (v.1.10.1, Virtanen et al., 2020). We optimized for relevant priors ($p(x)$), transition probabilities ($p(x|x_{t-1})$) and internal likelihood variances that best capture response behavior. A total of 12 parameters was optimized. The cost function was given by

$$c = q \cdot \log\left(\frac{q}{p(ext)}\right) + (1-q) \cdot \log\left(\frac{(1-q)}{1-p(ext)}\right),$$

with $q = \frac{\Sigma(r_t{==}1)}{N}$, where $p(ext)$ is the probability of inferring an external cause at probe presentation and r_t the participant's response (0= no detection, 1= detection). Optimization was terminated after convergence to six digits.

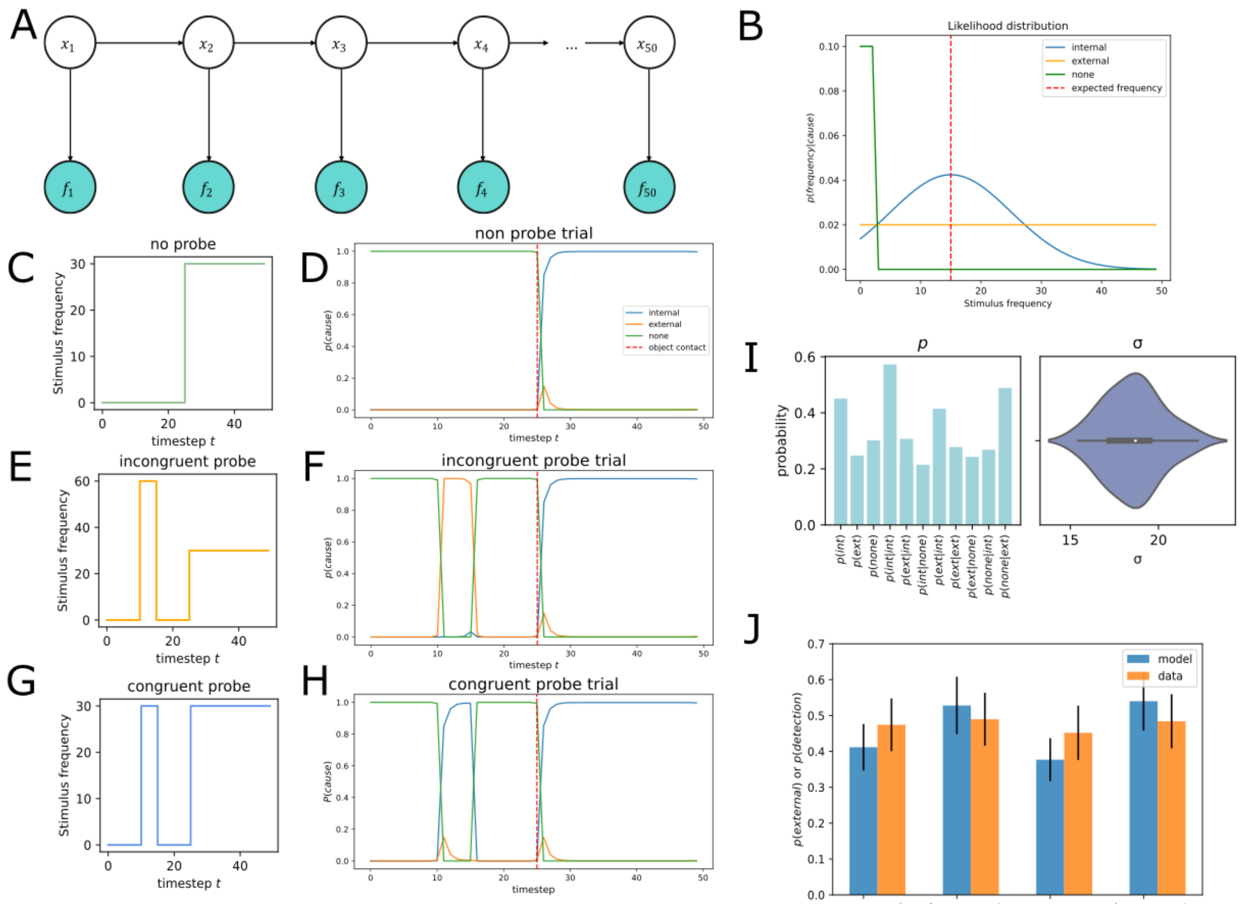

Figure 1. Results from simulations (A-H) and optimization (I,J)

Results

Simulations In non-probe trials, 'none' stimulation is inferred before touching the textured surface, and internally, i.e. movement generated sensory input is inferred during stroking (Fig. **1D**). Congruent probes (Fig. **1G**) are inferred as internally caused (Fig. **1H**) which we equate with the attenuation of external sensory input, whereas incongruent probes (Fig. **1E**) are inferred as externally generated (Fig. **1F**).

Model fitting After convergence, the optimizer yielded plausible results for all parameters of the generative model, where the largest inter-individual variability was observed for the motor noise (σ) parameter (Fig. **1I**). We find a good agreement between predicted and empirically observed detection events (plotted per trial type in Fig. **1J**)

Discussion.

We show that a BCI-based graphical model can capture hallmark features of SA during reaching. SA is tuned to action-derived predictions of what caused tactile input. The attribution of congruent probes to internal causes yields SA. Our model of SA may help elucidate the underlying mechanisms and contextualize contradictory findings where sensory facilitation, and not SA, is observed (van Kemenade et al., 2016).

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