Multisensory Soup with Bayesian Croutons

Why Bayesian Causal-Inference does not explain Body Ownership

In this paper, I contend that existing *Bayesian Causal Inference* (BCI) models do not yet explain how the sense of body ownership arises from multisensory integration, because they treat as primitive assumptions the very ingredients that a satisfactory explanation ought to ground. To motivate this critique, I situate body ownership within the broader notion of *bodily awareness*, understood as the set of experiences of one's own body grounded in a continuous stream of internal and external perceptual information (Vignemont, 2025). Most of the literature agrees that bodily awareness is rooted in multisensory experience. This idea is captured by the *multimodality thesis*, according to which bodily experiences (e.g., feeling one's legs crossed or locating one's hand) are constitutively multimodal (Vignemont, 2014; Vignemont, 2018). The leading account of this multimodality holds that bodily experiences arise from the *integrative binding* of body-related signals across sensory modalities, since different modalities provide partly redundant information about the same property (Vignemont, 2018). Such multisensory integration supports several subcomponents of bodily awareness, most notably the *sense of body ownership*—the experience of a body part as one's own (Tsakiris, 2017). However, how multisensory integration gives rise to body ownership remains a matter of ongoing debate.

The dominant framework for understanding this integration mechanism is the *Bayesian Causal-Inference* (BCI) (e.g. Chancel et al., 2022; Fang et al., 2019; Samad et al., 2015). I focus on its application on the rubber-hand illusion (RHI), a widely investigated phenomenon in which experimenters induce in the subject a sense of ownership toward a rubber hand by manipulating cross-modal stimulation (Botvinick & Cohen, 1998). BCI treats integrative binding as the outcome of a two-step causal inference. As a first step, the system estimates whether sensory cues (typically visual, tactile, and proprioceptive) originate from a common cause, on the basis of the cross-modal cues of spatial congruence (e.g., positional consistency; distance between the real and fake limb), temporal congruence (e.g., synchrony of stimulation), and semantic congruence (e.g., anatomical plausibility, hand-likeness, identity-related cues). If congruence is sufficient to support an inference of a common cause, the system generates the related *unity assumption* (Chen & Spence, 2017). As a second step, proprioception's *Immunity to Error through Misidentification* (IEM) supports identifying that cause with the subject's own body (see Vignemont, 2018), and the system accordingly adjusts cross-modal experience so as to further confirm the congruence established in the previous stage. The consequence of this adjustment process is the emergence of a sense of body ownership toward the object.

Both steps are argued to rely on *prior expectations*, which modulate both (i) aspects of the common-cause inference process—namely, how stringent the various forms of congruence must be, and by which criteria, in order to regard the stimuli as caused by the same object—and (ii) aspects of the integration process, namely, which reference points perceptual experience should be integrated toward and to what extent. The role of expectations of this kind in Bayesian-inspired models has often raised concerns in the critical literature, which has questioned whether their richness genuinely explains a cognitive phenomenon or instead merely postpones explanation (Bowers & Davis, 2012). This paper offers a critical argument targeting the role of such expectations in explaining how the sense of body ownership emerges.

First, I argue that the Bayesian explanation is *circular*, because the expectations it invokes already presuppose body ownership—exactly what the inferential process is supposed to deliver. Indeed, if IEM is already operative at the initial stage of common-cause assessment, and if it effectively functions as a prior to the effect that what is proprioceptively experienced must belong to one's own body, then ownership becomes little more than assent to a common cause whenever proprioception is among the relevant cues. On that construal, the ownership experience reduces to the question of which objects are proprioceptively experienced. And if that is right, the RHI would be hard to accommodate: if ownership is merely the identification of what is proprioceptively sensed and attributed to a single cause, there should be little room for a visually driven bias—whereas the paradigm is typically taken to involve precisely such a bias, consistent with visual dominance.

Second, it contends that these expectations are *explanatorily unstable*, insofar as they display features that make systematic investigation difficult:

(1) *Black-box problem* (Craver, 2006): neither the internal relations among the prior expectations nor the relations between them and the inferential outcome are specified. Instead, their role is often characterized merely by observing that manipulating a given expectation yields a different modulation of the illusion, which allows input–output prediction but not an explanation of why particular inputs produce those outputs.

(2) *Homunculus problem* (Margolis, 1980): the assumed priors are highly sophisticated and involve, beyond spatiotemporal congruence criteria, beliefs about human body anatomy, features of one's own body, affectively valanced expectations etc. In this respect, they risk positing an internal complex entity who has expectations, generates predictions, and forms hypotheses.

(3) *Interface problem* (see Burnston, 2021): the priors are so heterogeneous in format (e.g., topological, semantic, sensorimotor, and affective) that it becomes unclear how they interact so as to yield the perceptual outcome; an interface problem therefore has to be solved for the model to count as genuinely explanatory.

(4) *Bayesian soup problem*: In summary, the under-specification of priors makes the model vulnerable to ad hoc tuning "escape routes". If the model fails to predict an empirical result, one can simply add further priors taken to be relevant in order to accommodate the data, so that the set of priors resembles a soup to which ingredients can always be added if the taste is unsatisfactory.

In light of these difficulties, the paper argues that BCI models fall short of genuinely explaining how body ownership arises from multisensory integration, because the decisive explanatory work is effectively offloaded onto the model's background assumptions—above all, the posited prior expectations.

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