Inference to the Best Prediction

A Reply to Wanja Wiese

Anil K. Seth

Responding to Wanja Wiese's incisive commentary, I first develop the analogy between predictive processing and scientific discovery. Active inference in the Bayesian brain turns out to be well characterized by abduction (inference to the best explanation), rather than by deduction or induction. Furthermore, the emphasis on control highlighted by cybernetics suggests that active inference can be a process of "inference to the best prediction", leading to a distinction between "epistemic" and "instrumental" active inference. Secondly, on the relationship between perceptual presence and objecthood, I recognize a distinction between the "world revealing" presence of phenomenological objecthood, and the experience of "absence of presence" or "phenomenal unreality". Here I propose that world-revealing presence (objecthood) depends on counterfactually rich predictive models that are necessarily hierarchically deep, whereas phenomenal unreality arises when active inference fails to unmix causes "in the world" from those that depend on the perceiver. Finally, I return to control-oriented active inference in the setting of interoception, where cybernetics and predictive processing are most closely connected.

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1 Introduction

It is a pleasure to respond to Wanja Wiese's stimulating commentary (this collection), from which I learned a great deal. Much of what he says stands easily by itself, so here I select just a few key points which warrant further development in light of his analysis.

2 Active inference and hypothesis testing

A central claim in my target paper is that active inference, typically considered as the resolution of sensory prediction errors through action, should also (perhaps primarily) be considered as furnishing disruptive and/or disambiguatory evidence for perceptual hypotheses. This claim transparently calls on analogies with hypothesis testing in science (as well as on counterfactually-equipped generative models), and so invites comparisons with theoretical frameworks for scientific discovery, as Wiese nicely develops. In particular, Wiese notes that I do not "say much about what it takes to disconfirm or falsify a given hypothesis or model", inviting me to "provide a refined treatment of the relation between falsification and active inference" (this collection, p. 2). This is what I shall attempt in this first section.

2.1 The abductive brain

Wiese rightly says that a strict Popperian analogy for active inference is inappropriate since Popperian falsification relies on hypotheses that are derived deductively. Deductive inferences are *necessary inferences*, meaning that their falsification in turn falsifies the premises (theories) from which they derive. Active inference in the Bayesian brain is not deductive for two important reasons. First, as Wiese notes, Bayesian inference is inherently probabilistic so that competing hypotheses become more or less likely, rather than corroborated or falsified. Probabilistic weighting of hypotheses suggests a process of *induction* rather than deduction. Inductive inferences are *non-necessary* (i.e., they are not inevitable consequences of their premises) and are assessed by observation of outcome statistics, by analogy with classical statistical inference. Second, Bayesian reasoning pays attention not just to outcome frequencies but to properties of the explanation (hypothesis) itself, as captured by the slogan that (Bayesian) perception is the brain's "best guess" of the causes of its sensory inputs. This indicates that the Bayesian brain is neither deductive nor inductive but *abductive* (Hohwy 2014), where abduction is typically understood as "inference to the best explanation". In Bayesian inference, what makes a "best" explanation rests not only on outcome frequencies, but also on quantification of model complexity (models with fewer parameters are preferred), and by priors, likelihoods, as well as hyper-priors which may make some prior-likelihood combinations more preferable than others. Importantly, abductive (and inductive) processes are *ampliative*, meaning that they are capable of going beyond that which is logically entailed by their premises. This is important for the Bayesian brain, because the fecundity and complexity of the world (and body) requires a flexible and open-ended means of adaptive response.

So, the Bayesian brain is an abductive brain. But I would like to go further, recalling that active inference enables predictive *control* in addition to perception. This emphasis is particularly clear in the parallels with cybernetics and applications to interoception developed in the target article, where allostatic[1] control of 'essential variables' is paramount, and where predictive models are recruited towards this goal Conant & Ashby 1970; Seth 2013). In this light, active inference in the cybernetic Bayesian brain becomes a process of "inference to the best *prediction*", where the "best" predictions are those which enable control and homeostasis under a broad repertoire of perturbations.[2] It will be interesting to fully develop criteria for "best-making" in this control-oriented form of abductive inference.

2.2 Sophisticated falsificationism, active inference, and model disambiguation

Where does this leave us with respect to theories of scientific discovery? Strict Popperian falsification was already discounted as an analogy for active inference. At the other extreme, parallels with Kuhnian paradigm shifts also seem inappropriate since these are not based on inference whether deductive, inductive, or abductive. Also, such shifts are typically unidirectional: having dispensed with the Copernican worldview once, we are unlikely to return to it in the future. These two points challenge Wiese's analogy between paradigm shifts and perceptual transitions in bistable perception (see Wiese's footnote 12, this collection, p. 9). What best survives in this analogy is an appeal to hierarchical inference, where changes in "paradigm" correspond to alternations between hierarchically deep predictions, each of which recruit more fine-grained predictions which themselves each explain only part of the ongoing sensorimotor flux, under the hyper-prior that perceptual scenes must be self-consistent (Hohwy et al. 2008).

Wiese himself seems to favour Lakatos' interpretation of Popper, a "sophisticated falsificationism" where theories (perceptual hypotheses) can be modified rather than rejected outright, when predictions are not confirmed,

1 Allostasis: the process of achieving homeostasis.

2 There is an interesting analogy here to the overlooked "perceptual control theory" of William T. Powers, which says that living things control their perceived environment by means of their behavior, so that perceptual variables are the targets of control (1973).

and where hypotheses are not tested in isolation (more on this later). As Wiese shows, sophisticated falsification fits well with some aspects of Bayesian inference, like model updating. According to Lakatos, core theoretical commitments can be protected from immediate falsification by introducing "auxiliary hypotheses" which account for otherwise incompatible data (1970). The key criterion - in the philosophy of science sense - is that these auxiliary hypotheses are *progressive* in virtue of making additional testable predictions, as opposed to *degenerate*, which is when the core commitments become less testable.[3] This maps neatly to counterfactually-equipped active inference, where hierarchically deep predictive models spawn testable counterfactual sensorimotor predictions which are selected on the basis of precision expectations, and which lead to effective updating (rather than "falsification") of perceptual hypotheses. As Wiese notes, a good example of this is given by Friston and colleagues' model of saccadic eye movements (Friston et al. 2012). When it comes to model comparison, sophisticated falsification may even approximate some aspects of abductive inference: "Explaining away is another example of sophisticated falsification. Even when two or more models are compatible with the evidence … there can be reason to prefer one of them and reject the other" (Wiese this collection, p. 7). This strongly recalls Bayesian model comparison and "inference to the best explanation", if not its control-oriented "inference to the best prediction" form.

One important clarification is needed about Wiese's interpretation of model comparison, highlighting the critical roles of action and counterfactual processing. Wiese rightly emphasizes the important insight of Popper and Lakatos that hypotheses are never tested in isolation, mandating a process of comparison among competing models or hypotheses. However, he implies a sequential testing of each hypothesis: "balloons being launched and then shot done, one by one" (see Wiese this collection, p. 6). This is quite different from the interpretation of model comparison pursued in my target article, where multiple models are considered in parallel, and where counterfactual predictions are leveraged to select the action (or experiment) most likely to *disambiguate* competing models. In Bayesian terms this is reflected in a shift towards model comparison and averaging (FitzGerald et al. 2014; Rosa et al. 2012), as compared to inference and learning on a single model. Bongard and colleagues' evolutionary robotics example was selected precisely because it illustrates this point so well (Bongard et al. 2006). Here, repeated cycles of model selection and refinement lead to the prescription of novel actions that best disambiguate the current best models (note the plural). Indeed, it is the repeated refinement of disambiguatory actions that gives Bongard's starfish robot its compelling "motor babbling" appearance. To reiterate: different actions may be specified when the objective is to disambiguate multiple models in parallel, as compared to testing models one-at-a-time. In the setting of the cybernetic Bayesian brain this example is important for two reasons: it underlines the importance of counterfactual processing (to drive the selection of disambiguatory actions) and it emphasizes that predictive modelling can be seen as a means of control in addition to discovery, explanation, or representation. In this sense it doesn't matter how accurate the starfish self model is – what matters is whether it works.

2.3 Science as control or science as discovery?

The distinction between explanation and control returns us to the philosophy of science. Put simply, the views of Popper, Lakatos, and (less so) Kuhn, are concerned with how science reveals truths about the world, and how falsification of testable predictions participates in this process. Picking up the threads of abduction,

3 An important application of this idea is to the Bayesian brain itself as a scientific hypothesis. A concern about the Bayesian brain hypothesis is that it can be insulated from falsification by postulating convenient (typically unobservable) priors, much like adaptationist explanations in evolutionary biology can be critiqued as "just so" stories. The key question, not answered here, is whether neural mechanisms implement (approximations to) Bayesian inference, or whether Bayesian concepts merely provide a useful interpretative framework. In the former case one would require the Bayesian brain hypothesis to be progressive not degenerate.

control-oriented active inference, and "inference to the best prediction", we encounter the possibility that theories of scientific discovery might themselves appear differently when considered from the perspective of control. Historically, it is easy to see the narrative of science as a struggle to gain increasing control over the environment (and over people), rather than a process guided by the lights of increasing knowledge and understanding.[4] A proper exploration of this territory moves well beyond the present scope (see e.g., Glazebrook 2013). In any case, whether or not this perspective helps elucidate scientific practice, it certainly suggests important limits in how far analogies can be taken between philosophies of scientific discovery and the cybernetic Bayesian brain.

3 Perceptual presence and counterfactual richness

The second part of Wiese's commentary picks up on the issue of *perceptual presence*, which in my target article was associated with the "richness" of counterfactual sensorimotor predictions (see also Seth 2014, 2015b). Wiese makes a number of connected points. First, he rightly notes an ambiguity between objecthood and presence in perceptual phenomenology, as presented in my target article (Seth this collection) and in Seth (2014). Second, he introduces the notion of *causal encapsulation* as a third phenomenological dimension, complementing counterfactual richness and perspective dependence. He spends some time developing examples based on cognitive phenomenology and mental action to illustrate how these dimensions might relate. Here, I will focus on the relationship between presence and objecthood from the perspective of counterfactual predictive processing – or more specifically the theory of " Predictive Processing of SensoriMotor Contingencies" (PPSMC; Seth 2014, 2015b).[5]

4 The continually increasing pressure to justify research in terms of "impact" – especially when seeking funding – highlights one way in which an emphasis on control (rather than discovery) is realized in scientific practice.

5 See also my response (Seth 2015b) to commentaries on (Seth 2014), which focuses on this issue.

3.1 Presence and objecthood together

As Wiese notes, when visually perceiving a real tomato (figure 1A) there is both a sense of *presence* (the subjective sense of reality of the tomato) and of *objecthood* (the perception that a (real) object is the cause of sensations). Importantly, while distinct, these properties are not independent. There is a "world-revealing" dimension to perceptual presence which is closely aligned with the experience of an externally-existing object: "How can it be true … that we are perceptually aware, when we look at a tomato, of the parts of the tomato which, strictly speaking, we do not perceive. This is the puzzle of perceptual presence" (Noë 2006, p. 414).

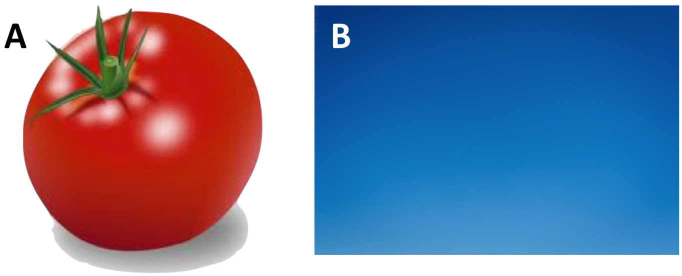

Figure 1: A. An image of a tomato. **B**. An image of a clear blue sky.

How does this object-related world-revealing presence come about? In predictive processing (and by extension PPSMC), objecthood depends on predictive models encoding hierarchically deep invariances that accommodate complex nonlinear mappings from (object-related, world-revealing) hidden causes to sensory signals (Clark 2013; Hohwy 2013). There is a reciprocal dependency here between hierarchical depth and counterfactual richness, because (i) hierarchically deep invariances in generative models enable precise predictions about rich repertoires of counterfactual sensorimotor mappings, and (ii) counterfactual richness can scaffold the acquisition of hierarchically deep invariant predictions. One might even say that hierarchically deep invariances are partly *constituted* by (possibly latent) predictions of counterfactually rich sensorimotor mappings (Seth 2015b). These dependencies indicate that objecthood and world-revealing presence depend on *expectations about counterfactual richness*, rather than counterfactual richness *per se*. Altogether, counterfactually-informed active inference enables the extraction and encoding of hierarchically deep hidden causes of sensory signals. In virtue of hierarchical depth, these inferred causes will also be *perspective invariant*, in the sense that they will have been separated from those causes that depend on on actions (or other properties) of the perceiver (see Wiese this collection, p. 11). In short, to the extent that objecthood and perceptual presence go together, so do hierarchical depth (encoding world-revealing invariances) and (expected) counterfactual richness.

3.2 Presence and objecthood apart

So far so good, but it is evident that presence and objecthood do not *always* go together (Di Paolo 2014; Froese 2014; Madary 2014), a phenomenological fact which requires further analysis (Seth 2015b). Presence without objecthood is exemplified in vision by the experience of a uniform deep blue sky (Figure 1B), and is also characteristic of non-visual modalities like olfaction (Madary 2014). The visual impression of a blue sky, or the tang of briny sea air, both seem perceptually present but without eliciting any specific phenomenology of objecthood. At the same time, the corresponding predictive models are likely to be hierarchically shallow and counterfactually poor: there is not much I can do (besides closing my eyes or looking away) to alter the sensory input evoking a blue-sky experience, and the inferred hidden causes are unlikely to lie behind multiple inferential layers. Hierarchical shallowness may explain the lack of phenomenal objecthood, but why isn't there also a lack of perceptual presence?

Blue-sky-experiences (and olfactory scenes) actually *do* lack the world-revealing presence associated with objecthood. But they do not appear *phenomenally unreal* in the sense that perceptual afterimages and synaesthetic concurrents are experienced as unreal. In PPSMC, phenomenal unreality can arise from an inferential failure to separate hidden causes in the world, from those that depend on actions (or other properties) of the perceiver (Seth 2015b). This in turn emerges from violations of counterfactual predictions. For example, consider how saccadic eye movements engage counterfactual predictions. Perceptual afterimages track eye movements, violating counterfactual predictions associated with world-revealing hidden causes that rest on active inference. In contrast, counterfactual predictions associated with blue skies are less amenable to disconfirmation by eye movements, so (non-object-related) perceptual presence remains.[6]

Summarizing, perceptual presence, as an explanatory target, can be refined into (i) a *world-revealing presence* associated with objecthood and hierarchical depth, and (ii) a *phenomenal unreality* arising from a failure to inferentially separate hidden causes in the world from those associated with the perceiver. Both rely on counterfactual processing, and so both call on active inference. Perspective invariance is also implicated in objecthood (through hierarchical depth) and phenomenal unreality (through isolating worldy causes), suggesting that this dimension may not be as separable from counterfactual richness as proposed by Wiese (this collection, p. 13). But is that all there is to presence?

3.3 Causal encapsulation and embodiment

Wiese distinguishes three dimensions to perceptual presence: counterfactual richness (vs. poverty), perspective invariance (vs. dependence), and causal encapsulation (vs. integration). The third of these, causal encapsulation, is perhaps the hardest to pin down. The idea as I understand it, is that a representation (predictive model) is causally encapsulated if it is inferentially isolated from other hidden causes; by contrast it is causally *open* or *integrated* if it expresses a rich set of relations to other inferred

6 Phenomenal unreality on this story corresponds to a loss of "transparency" as described by (Metzinger 2003). For Metzinger, transparency is lost – and phenomenal unrealness results – when the "construction process" underlying perception becomes available for attentional processing. This maps neatly on a failure to inferentially unmix world-related from perceiver-related hidden causes – see Seth (2015b) for more on this.

causes. So, a predictive model underlying the experience of a tomato may be causally integrated with that underlying the experience of the table on which it lies, and the hand (maybe my hand), which is poised to reach out and pick it up. Here, there may be a relation between causal encapsulation/integration and the inferential unmixing of perceiver-related and world-related hidden causes: a failure to separate these causes would presumably prevent rich causal integration with other hidden causes in the world.

The concept of causal encapsulation highlights another interesting aspect of Wiese's commentary: the idea that counterfactual predictions may not always encode sensorimotor contingencies: "it might be equally relevant to encode how sensory signals pertaining to the tomato would change if the wind were to blow … or if the tomato were to fall down" (Wiese this collection, p. 11). While such extra-personal causal contingencies may be salient in many cases, I see them as secondary to sensorimotor body-related counterfactual predictions. By definition they do not involve active inference: I have to wait for the wind to change direction (though perhaps I might move to get a better view). This means that many central features of active inference discussed here – its relation to predictive control, homeostasis, and counterfactually-informed model disambiguation – do not apply.

The body re-emerges here as central, this time as a ground for the generation of counterfactual predictions. Specifically, bodily constraints shape counterfactual predictions since they place limits on how actions can be deployed in intervening upon the (inferred) causes of sensory input. This suggests that changing action repertoires would alter experiences of presence. Wiese raises out-of-body-experiences and dream experiences as a relevant context (this collection, p. 15), where subjects sometimes identify their first-person-perspective, not with a body, but with an unextended point in space. I agree with him that examining world-revealing presence in these situations would be fascinating, if extremely difficult in practice.

The body is of course not only a source of counterfactual predictions, but also the target of counterfactually-informed active inference, both for representation (exemplified by the rubber-hand-illusion, as mentioned by Wiese) and for control.[7] As emphasized in the target article, control-oriented active inference is particularly significant for *interoception*, where predictive modelling is geared towards allostasis and homeostasis rather than accurate representation (see also Seth 2013). Returning the focus to interoceptive inference raises a host of intriguing questions, which can only gestured at here. One may straightaway wonder how counterfactual aspects of interoceptive inference shape the "presence" of emotional and body-related experiences. Is it possible to have an emotional experience lacking in "affective presence" – and what is the phenomenological correlate of "objecthood" for interoceptive experience? Other interesting questions are how precision weighting sets the balance between representation versus control in active interoceptive inference, and what it means to isolate "wordly" causes when both the means and the targets of active inference are realized in the body. These are not just theoretical questions: advances in virtual reality (Suzuki et al. 2013) and in methods for measuring interoceptive signals (Hallin & Wu 1998) promise real empirical progress on these issues.

4 Conclusions

This response has been shaped by Wiese's perspicuous focus on the philosophy of science and on the phenomenology of perceptual presence. My response to the first topic was to frame the Bayesian brain in terms of *control-oriented ab-*

7 Wiese, when discussing König's FeelSpace project (Kaspar 2014), interprets PPSMC as saying that increased practice with the FeelSpace compass belt – and hence increased counterfactual richness– would lead to "increased perceptual presence (for the belt, or the vibrations, or the hip/waist, etc.)" (Wiese this collection, p. 17). I see things differently. The counterfactual predictions, while mediated by the belt, relate to hidden causes in the world (e.g., magnetic north). In fact, PPSMC says that FeelSpace practice would lead to hierarchically deep and counterfactually rich models of how "magnetic north" impacts on belt vibrations and the like, leading to increased world-revealing presence for these worldly causes but diminished perceptual presence of the tactile stimulation itself. Still, the FeelSpace project certainly provides a fertile empirical testbed for the ideas raised here.

duction, where falsification is replaced by "inference to the best prediction" as a criterion for progress. I also reinforced the dependency between active inference and counterfactual processing, which underpins the important case of disambiguatory active inference in Bayesian model comparison. With respect to perceptual presence I proposed a distinction between world-revealing presence and phenomenal unreality (Seth 2015b). World-revealing presence corresponds to objecthood and is associated with hierarchical depth, expected counterfactual richness, and perspective invariance of perceptual hypotheses. Phenomenal unreality transpires when perceptual inference fails to unmix world-related from perceiver-related causes; this corresponds to a loss of "phenomenal transparency" (Metzinger 2003) and depends on violation of counterfactual sensorimotor predictions. Space constraints prevented me considering Wiese's discussion of the "presence" of cognitive phenomenology, like abstract mathematical and philosophical thinking, in these terms. There is of course a rich literature in linking such phenomena to the body (Lakoff & Nunez 2001), and hence perhaps to active inference where the concept of a "mental action" becomes critical (O'Brien & Soteriou 2009). Space constraints also prevented Wiese from elaborating on interoception, which I consider the most interesting setting for control-oriented active inference, in virtue of the cybernetics-inspired emphasis on homeostasis and allostasis. Interesting questions emerge here about how counterfactual processing plays into the phenomenology of interoceptive experience.

Cognitive scientists have long argued for a continuity between perception and action (Dewey 1896). To close, I suggest thinking instead of a continuum between *epistemic* and *instrumental* active inference. This is simply the idea that active inference – a continuous process involving both perception and action – can be deployed with an emphasis on predictive control (instrumental), or on revealing the causes of sensory signals (epistemic). This process intertwines interoception, proprioception, and exteroception, and autonomic and motoric action, with the balance always delicately orchestrated by precision optimisation and counterfactual processing. Putting things this way provides a new way to link "life" and "mind" (Godfrey-Smith 1996) and may help reveal the biological imperatives underlying perception, emotion, and selfhood.

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