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Knowing when to stop: Aberrant precision and evidence accumulation in schizophrenia

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ABSTRACT

Predictive coding and active inference formulations of the dysconnection hypothesis suggest that subjects with schizophrenia (SZ) hold unduly precise prior beliefs to compensate for a failure of sensory attenuation. This implies that SZ subjects should both initiate responses prematurely during evidence-accumulation tasks and fail to inhibit their responses at long stop-signal delays. SZ and healthy control subjects were asked to report the timing of billiards-ball collisions and were occasionally required to withhold their responses. SZ subjects showed larger temporal estimation errors, which were associated with premature responses and decreased response inhibition. To account for these effects, we used hierarchical (Bayesian) drift-diffusion models (HDDM) and model selection procedures to adjudicate among four hypotheses. HDDM revealed that the precision of prior beliefs (i.e., starting point) rather than increased sensory precision (i.e., drift rate) drove premature responses and impaired response inhibition in patients with SZ. From the perspective of active inference, we suggest that premature predictions in SZ are responses that, heuristically, are traded off against accuracy to ensure action execution. On the basis of previous work, we suggest that the right insular cortex might mediate this trade-off.

1. Introduction

This paper evaluates a prediction of the dysconnection hypothesis (Friston, 1998; Friston et al., 2016) about aberrant sensory precision and compensatory effects on the precision of prior beliefs. We pursue this using the temporal estimation of unfolding visual events. The dysconnection hypothesis suggests that the psychopathology of schizophrenia (SZ) is mediated neurophysiologically by deficient modulations of synaptic gain or excitation-inhibition balance, thought to be caused by abnormal NMDA and dopaminergic neurotransmission (Laruelle et al., 2003). From a neurocomputational perspective, the hypothesis calls on the theoretical tenets of predictive coding (Friston and Kiebel, 2009; Rao and Ballard, 1999) and active inference (Friston et al., 2011).

Predictive coding equips the dysconnection hypothesis with a functional link between sensory precision and synaptic gain. Briefly, in predictive coding, the brain generates predictions at various levels in the cortical hierarchy. Higher levels send predictions to lower levels, which then reciprocate prediction errors (PEs) to higher levels, minimizing PEs and optimizing the ensuing predictions. Crucially, it is thought that the brain weighs PEs based on their reliability, or precision, which is thought to be reflected in the synaptic gain of neuronal populations reporting PEs (Friston, 2008). Put simply, a large synaptic gain represents precise ascending PEs, and vice versa.

Crucially, for PEs to optimize predictions effectively, they must be afforded by the appropriate precision; i.e., assigned the right degree of confidence. This is particularly important in hierarchical inference, where the precision of PEs at each level of the hierarchy determines the balance between prior beliefs and sensory evidence during evidence accumulation. An imbalance between sensory and prior precision can, in principle, lead to false perceptual (e.g., hallucinations) and conceptual inference (e.g., delusions), see also Moritz et al. (2015). The synaptic implementation of precision or synaptic gain control is therefore crucial for a veridical grip on the world, where it forms the computational homologue of attention (Feldman and Friston, 2010). The control of sensory precision is also particularly important for action.

In active inference, actions are prescribed by descending proprioceptive predictions that engage classical reflex arcs. These descending predictions provide the equilibrium or set points for motor reflexes that realize the intended or predicted movement (Adams et al., 2013a). However, this requires the attenuation of sensory (exteroceptive) PEs that would otherwise allow ascending (proprioceptive) PEs to revise

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predictions about the impending action. This attenuation is thought to be the computational homologue of sensory attenuation (Brown et al., 2013). In this sense, sensory attenuation is necessary for action. This follows from the fact that action is driven by descending predictions of what "I would sense if I made this movement". A failure to attenuate proprioception would therefore preclude movement because prevents a suspension of attention to sensory evidence that "I am not moving". Simulations of a failure to attenuate sensory precision produce bradykinesia and psychomotor poverty (Brown et al., 2013) and provide a straightforward explanation for empirical phenomena in conditions like Parkinson's disease and SZ (Adams et al., 2012; Adams et al., 2013b; Hughes et al., 2013; Oestreich et al., 2015).

A failure to attenuate sensory precision and a compensatory increase in prior precision has been proposed to explain hallucinations and delusions respectively (Adams et al., 2012; Bastos-Leite et al., 2015; Brown et al., 2013; Fogelson et al., 2014; Friston et al., 2016; Powers et al., 2017). The basic idea is that people with SZ are unable to attenuate the precision of sensory PEs; thereby exposing themselves to sensory evidence that cannot be ignored. This aberrant precision then induces a compensatory increase in the precision of PEs that underwrites prior beliefs at higher levels of the perceptual hierarchy. This aberrant precision formulation accounts for two fundamentally different sorts of false inference in SZ that can be thought of in terms of false negatives and false positives. A failure to attenuate sensory precision leads to negative symptoms and soft neurological signs in SZ (e.g., psychomotor poverty, resistance to illusions, failures of slow pursuit, attenuating mismatch negativity responses, etc., Adams et al., 2013b) that can be understood as a failure to elicit predictions (of sensations or movements) that are informed by prior beliefs. On the other hand, a compensatory increase in prior precision is thought to lead to positive symptoms (e.g., hallucinations and delusions, Powers et al., 2017) that represent prior beliefs that are afforded too much confidence. In short, the precision of sensory PEs, relative to prior beliefs, furnishes a theoretical framework for explaining negative and positive symptoms in SZ and testing predictions about accompanying cognitive and behavioral sequelae. Crucially, this framework can be related gracefully to evidence-accumulation schemes through precision. As we will see below, sensory precision controls the sensitivity to sensory evidence and therefore the rate at which it is accumulated (FitzGerald et al., 2015a; FitzGerald et al., 2015b).

Simulating, measuring, and modeling oculomotor behavior when SZ subjects track a moving object, suggests that aberrant sensory precision precludes the acquisition of prior beliefs based upon regular motion patterns (Adams et al., 2015; Adams et al., 2016; Adams et al., 2012). These prior beliefs normally allow people to predict *when* a moving object will reach a target (i.e., temporal estimation) (Barnes and Donelan, 1999; Fukushima et al., 2013; Heinen et al., 2005; Missal and Heinen, 2017). Interestingly, impaired temporal estimation is characteristic of subjects with SZ (Alústiza et al., 2017).

A task in which the aberrant encoding of sensory precision could affect this sort of temporal inference is the "time to collision" (TTC) task (i.e., estimating the time of the collision of a moving object with a stationary object, Fig. 1). Healthy subjects predict a TTC that is too early (indexed by a short response time, RT) when they can no longer track the motion of the moving object — and are therefore unable to update their beliefs about its trajectory. In this situation, their estimates are based largely on their prior experience. For example, their experience of responding prematurely leads them to believe that a loss will occur (in this sort of experimental setting, prior beliefs are usually induced by task instructions). This results in a large temporal estimation error (TEE); namely, RT minus collision time (Limongi and Pérez, 2017). It follows, that if aberrant precision control in SZ leads to a compensatory increase in the precision of prior beliefs, we should find a similar effect (i.e., large absolute TEEs or short RTs), even when visual motion information is available.

Predicting the TTC requires not only tracking the motion of the moving object but also preparing a response, putting it "on hold", and "releasing" it a few milliseconds before the collision (to compensate for sensorimotor delays). Placing prepared actions "on hold", requires response inhibition (Los, 2013). Interestingly, response inhibition is impaired in SZ (Hughes et al., 2012; Thakkar et al., 2011; Zandbelt et al., 2011). It is therefore possible that premature responses in SZ are associated with impaired response inhibition — and that this is associated with aberrant precision control.

Response inhibition is described phenomenologically by the (independent) horse-race (IHR) model (Logan and Cowan, 1984; Logan et al., 2014). In this model, two processes (stop and go) independently run towards a decision threshold. Each process comprises a RT (the RT_{go} and the stop-signal RT, SSRT), and the first process reaching the threshold wins the race. The delay between the go and stop signals (the stop-signal delay, SSD) affects the conclusion of the stop process relative to the conclusion of the go process. When $RT_{go} > SSRT + SSD$ the agent inhibits the ongoing response whereas when $RT_{go} < SSRT + SSD$ the agent fails to inhibit the response. The model assumes that go and stop processes are independent in terms of context (the same

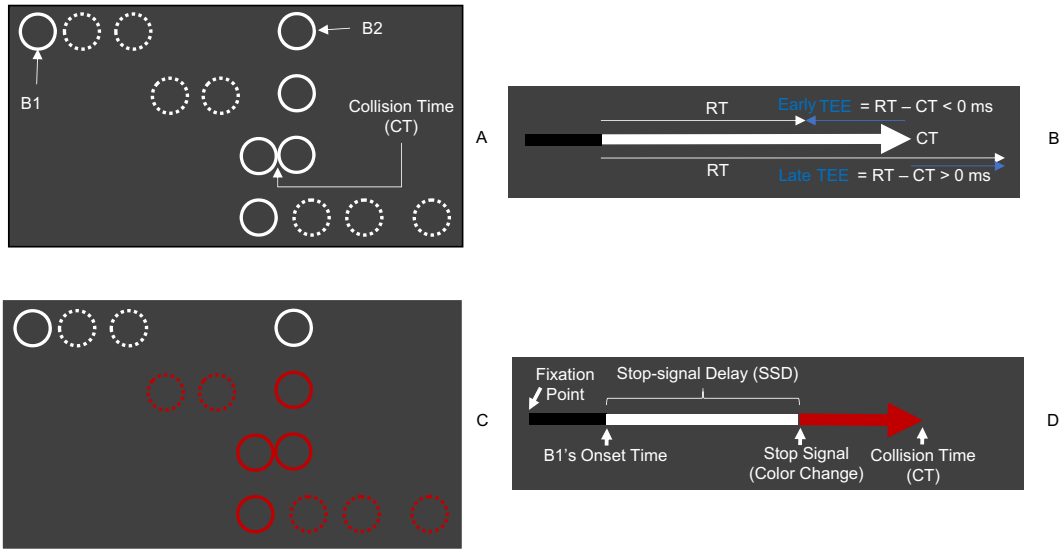

Fig. 1. Response inhibition in TTC estimations. Go trial (A) and its timeline (B). Stop trial (C) and its timeline (D).

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