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Commentary

Using Corollary Discharge and Predictive Coding to Understand False Sensations and Beliefs

Rylee Brower, Haley R. Wang, Sonia Bansal, and Wilsaan M. Joiner

In psychotic disorders like schizophrenia (SZ), hallucinations and delusions are the most characteristic symptoms and are often how the disorder is first detected. Hallucinations and delusions are highly distressing experiences that involve distortions in reality, and though they often co-occur, they represent distinct symptoms. Hallucinations are perceptual abnormalities (e.g., hearing voices or seeing things that are not present); delusions are false beliefs about the world that are rigidly held with strong conviction despite contradictory evidence (e.g., being sure that aliens are watching). These experiences and beliefs are often intertwined, such that a delusion might be an attempt to explain a hallucinatory experience or strange perception. Considering the phenomenological differences and multifaceted manifestations of false sensations and beliefs, understanding the underlying neurobiological abnormalities remains elusive. What is the common link across people who experience these symptoms? There are several lines of explanation, but could there be one all-encompassing faulty mechanism that explains both? We describe two prevalent frameworks that have been used to explain these aberrant experiences.

The first framework is corollary discharge (CD). Based on theoretical, computational, and physiological work, CD is a copy of the neural movement signals that enable action (e.g., initiating speech or moving the eyes). Concurrent with the motor command, the CD is sent from the motor areas of the brain to the associated sensory areas. This prepares the brain for the incoming sensations caused by the movement, leading to an expectation of impending sensory information. When the actual sensory input from movement occurs it is compared with the expectation created by the CD. If the input and the expectation match, a net cancellation occurs, resulting in reduced sensation. This matching between expected and actual sensation allows the distinction of action outcomes as being self-generated, giving a sense of control and ownership to sensations resulting from self-generated actions. Failures in sensory-predictive mechanisms (1) across modalities may lead to symptoms of psychosis underlain by aberrant sense of agency.

Using electroencephalography in humans, Ford *et al.* (2,3) have demonstrated the CD mechanism for auditory processing. The strength of the neural response to an auditory stimulus is reflected by the amplitude of the N1 component of an event-related potential. Using variations of a voice recording and playback (talk–listen) paradigm it has been shown that N1 is commonly reduced in response to spoken (self-generated) compared with played-back vocalizations. In approximately 14 studies [for review, see Whitford (4)], it has been demonstrated that patients with SZ, as well as patients with bipolar disorder with psychotic features and schizoaffective disorder, manifest lower levels of N1 suppression to their own speech compared with healthy control subjects, therefore providing strong support for the CD framework in psychosis (2,5). In addition, in a task where subjects pressed a button to hear a tone, patients with SZ failed to suppress N1 as strongly as control subjects (3). However, these studies do not consistently find correlations between N1 suppression and symptom severity; only one study (5) found a negative correlation between hallucinations and N1 suppression. Perhaps CD dysfunction is not directly tied to symptom activity but rather is present in psychosis more broadly. In the auditory system, the idea that CD dysfunction results in hallucinations rests on the assumption that the act of thinking (i.e., inner speech) functions similarly to motor actions. However, in the visual system, where the CD mechanism contributes to oculomotor plans and perception, there is evidence that CD deficits in patients with SZ are associated with symptoms and an aberrant sense of agency. Similarly, in the somatosensory system, disturbances in action inference, agency attribution, and distinction of self-sensations versus external sensations are observed across the psychosis spectrum. Therefore, this framework theorizes that across sensorimotor modalities, endogenous neural activities interpreted as coming from the external environment may result in hallucinations and delusions of influence (6).

The second framework is predictive coding (PC), which is explained as a Bayesian inference model (7)—i.e., the brain uses a hierarchy for prediction generation and response to stimuli. Humans hold expectations about how the world will be experienced based on experiences (i.e., priors) generated in a higher level of the cortical hierarchy. When a sensory input occurs, the prior moves down through the levels and is compared with the sensory data (likelihood) and a prediction error (PE) results. The amount of influence the prior and the likelihood have on the PE is weighted by how "precise" they are—that is, how likely they are to be accurate. If priors are more precise, they are more heavily weighted; inversely, if precision is decreased, incoming sensory information has the most influence. When the prior and likelihood match up closely, the neural response is dampened. When they do not, the PE updates the overall model's probability prediction for the event for the next time it is encountered, moving back up the hierarchy (8).

Psychotic experiences are explained in this framework as an incorrect weighting of priors caused by fluctuations in neuromodulators (e.g., dopamine and *N*-methyl-D-aspartate receptor). According to this work, delusions arise as a function

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of overemphasizing sensory data and underweighting priors, meaning more experiences violate expectations and create surprise. It is known that more attention is paid to surprising stimuli than to expected stimuli, and this extra attention feeds into associative learning. In psychosis, typically ordinary stimuli are distinguished as surprising, and some significance of unusuality becomes attached to a commonplace experience, creating and deepening delusions. Conversely, hallucinations may arise from strong priors, overweighting previous experiences to create sensory material that does not actually exist externally (8).

Using functional magnetic resonance imaging, Corlett *et al.* (9) found that activation of the right prefrontal cortex (rPFC) was reliably associated with PE processing. In healthy individuals, greater rPFC activation was observed when expectations were violated and a PE occurred. Patients with SZ did not exhibit typical PE-related rPFC activation; neural signals were reduced in response to unexpected trials and increased in response to predicted events. In addition, higher ratings of unusual thought content score on the Brief Psychotic Rating Scale were associated with lower activation present in the rPFC during surprising conditions (9). While this PC framework has gained much traction in the field of neuropsychiatry, more work needs to be done to investigate the idea of stronger priors in psychotic disorders.

Though both PC and CD attempt to explain aberrant experiences in psychosis, they do not yet fit together. In the context of psychosis, one framework conceptualizes hallucinations as a decrease in CD creating a lack of prediction, where PC would require a stronger prior, overwhelming incoming sensory data. In this sense, the frameworks are direct opposites. However, more empirical experiments should be conducted to examine both theories and their interconnections. A potential reconciliation could be guided by the level at which CD is disrupted—aberrant PEs may have disparate consequences depending on whether they are more proximal or distal to sensory input. CD may act first, then PC follows if this fails. For example, perhaps when the CD-based biological mechanisms that predict self-generated sensation are imprecise, expectations from experience will fill the gap, and a strong prior will overcome sensory data to create a false percept.

Even if these two theories fit together, there are many questions left unaddressed by both. CD may explain some of the deficits stemming from sensorimotor systems (e.g., auditory vocal hallucinations) and PC may also include an explanation for cognitive dysfunction and belief formation (e.g., delusions), but neither explains the complete range and neurodevelopmental course of symptoms that are commonly found in psychosis. These may represent only a piece of the puzzle—and in this case, more exploration into how these frameworks fit into the context of the overall disorder in concert with the other neurocognitive symptoms must be addressed. Similarly, although there are core symptoms, each clinical presentation of SZ is unique. For example, some patients with SZ may experience delusions but not hallucinations and vice versa, while others experience both. Although there are commonly expressed psychotic beliefs, each patient carries an individual set of aberrant experiences. While PC leaves some room for subjectively unique psychotic experiences in individuals because of the weighting of endogenous predictions based on individual experiences, more research is required to understand what stimuli violate predicted expectations strongly enough to create aberrant experiences while others warrant no special attention. In addition, although there are differences between groups in both N1 suppression and rPFC activation and various neural signals in other modalities, it is imperative to explain whether these abnormal brain mechanisms result from psychosis or are more causal.

Recent studies encompassing human neurophysiology, neuroimaging, symptom assessment, tool development, behavioral psychophysics, and computational modeling approaches are all promising in answering complicated questions about processes of which we have limited understanding. Much further exploration is required to more definitively support these frameworks. To that end, the visual and oculomotor systems may provide an advantageous modality to investigate the mechanistic properties of PC and CD alike (10). Owing to the relatively more comprehensive understanding of visual processing and eye movement control, neural activity could be more accurately attributed to its true location and purpose, and dysfunction more clearly and confidently defined.

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Article Information

From the Departments of Neurobiology, Physiology and Behavior (RB, HRW, WMJ), University of California, Davis, Davis, and the Department of Neurology (WMJ), University of California, Davis, Sacramento, California, and the Maryland Psychiatric Research Center (SB), Department of Psychiatry, University of Maryland School of Medicine, Baltimore, Maryland.

Address correspondence to Wilsaan M. Joiner, Ph.D., University of California, Davis, Departments of Neurobiology, Physiology and Behavior and Neurology, 1 Shields Avenue, Davis, CA 95616; E-mail: wmjoiner@ucdavis.edu.

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