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Neural Mechanisms for Prediction: From Action to Higher-Order Cognition

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Review of Kilteni and Ehrsson.

Our perception of the world is not entirely veridical. Instead, theoretical, neuroimaging, and behavioral research has shown that we actively process sensory information, using our prior knowledge to form expectations and influence what we ultimately perceive. One attractive hypothesis regarding why the brain actively interprets the world, rather than senses it as is, is to increase efficiency in perception. Our neural resources are limited; therefore, the brain must decide how to prioritize unexpected input which is likely more informative. To do this, the brain uses prior knowledge to construct internal models and predict what information it may encounter. By comparing these predictions to actual input, we can quickly attend to the most important aspects of our environment, with the ultimate goal of optimizing context-dependent behavior.

In a recent study, Kilteni and Ehrsson (2020) examined how prior knowledge and expectations influence perception in the domain of self-generated touch. Previous research has shown that sensations arising from our own movements, which are highly predictable, are attenuated, allowing us to differentiate the sensory signals produced by the body from those produced by the outside world. This is thought to be the reason that we are less responsive to self-tickling (Blakemore et al., 1999). To assess the neural mechanisms underlying perceived attenuation of self-generated touch, Kilteni and Ehrsson (2020) combined a psychophysical task with neuroimaging. The authors first assessed perceived intensity across participants using a "force-matching" task, in which participants reproduced an externally generated force applied to their body. As in previous research, the authors used a device that applies force, either externally generated or generated by the right hand, to a finger on the left hand, and asked participants to reproduce experienced forces. When performing such tasks, people typically apply more force than what was applied by the external device, suggesting that sensations arising from self-generated actions are attenuated and are therefore perceived as less intense. The authors went beyond previous work by directly disentangling attenuation of self-generated touch from the mere co-occurrence of movement and touch. They included two well-matched control conditions engineered to manipulate how likely touch is to be self-generated. In one condition, the distance between the hands was manipulated because touch is more likely to be "self-generated" if body parts are close together. In another condition, participants matched the applied force on the left hand via a "slider" controlled by the right hand, as a sliding movement is less likely to result in the type of sensation experienced by participants. The authors showed that participants apply less force in these conditions than in conditions in which touch was very likely self-generated. This illustrates that participants perceived touch in these conditions as more intense, and further illustrates that perception can be affected by how reliably our motor actions predict self-generated sensation.

Kilteni and Ehrsson (2020) extended their behavioral findings by investigating neural mechanisms underlying perceived attenuation of self-generated touch. Using fMRI, the authors isolated the specific neural effects of self-generated touch from externally generated touch, movement that does not result in touch, and movement that is unlikely to result in touch (by increasing the distance between the hands). Compared with externally generated touch, self-generated touch resulted in less activation in the left posterior cerebellum (lobule VI/crus I, ipsilateral to the touch) and bilateral secondary somatosensory regions. Importantly, as in the behavioral results, cerebellar activation during self-generated touch was lowest when the probability of touch being caused by the self was high, namely, when the hands were close together. This demonstrates that neural attenuation is highest when the sensory consequences of our actions are highly predictable and that more reliable expectations attenuate neural activation to a larger extent.

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A particular strength of the manuscript was the authors' ability to elucidate neural mechanisms of attenuation as they relate to perception of self-generated touch. Individual differences in participants' behavioral attenuation were reflected in functional connectivity between the posterior cerebellum (ipsilateral to the touch) and contralateral primary and bilateral secondary somatosensory areas. Participants with greater connectivity between the posterior cerebellum and somatosensory regions attenuated their perception of self-generated touch to a greater degree. Crucially, these functional connections were no longer significant when regressing out participants' perceptions, underscoring their importance to the perceived attenuation of self-generated touch, not just touch or movement alone. Kilteni and Ehrsson's (2020) results indicate that the expected sensory consequences of our own actions result in attenuation that is reflected in altered perception, reduced cerebellar activation, and increased cerebrocerebellar coupling.

Kilteni and Ehrsson's (2020) work suggests that the cerebellum may hold and operate predictions, and that expectation-driven perceptual attenuation is a product of cerebrocerebellar communication. The circuitry underlying this communication has been well studied: the cerebellar cortex receives information from the cerebral cortex via the pons and sends information back to the same region of cortex via the deep cerebellar nuclei and thalamus. In the case of movement, the cerebellum receives an "efference copy" of motor commands from the motor cortex and generates predictions of the sensory consequences of that movement. These predictions are used to compare anticipated with actual sensory consequences. A mismatch between the actual and anticipated sensory signals results in a sensory prediction error, which can be used to rapidly optimize current and future movement through reciprocal connections between cerebellum and motor cortex (Ito, 2008). A match between actual and anticipated signals can "cancel" incoming sensory information, resulting in attenuation. Although Kilteni and Ehrsson (2020) explored self-generated touch, the cerebellum is also involved in auditory and visual sensory attenuation via cerebrocerebellar connections with corresponding sensory areas. For example, individuals with cerebellar damage show reduced attenuation to self-generated auditory sounds (Baumann et al., 2015).

Cerebellar predictive mechanisms are also involved in perception of sensory events that are not self-generated. Studies in relatively large cerebellum-like structures of electric fish find sensory attenuation for predictable or repeated external events (Fuentes and Bastian, 2007), and humans with cerebellar lesions show impairments in predicting externally generated temporal regularities or changing velocities (Baumann et al., 2015). There is evidence that the cerebellum also uses other types of external inputs, including higher-order cognitive expectations, to produce sensory attenuation. Indeed, anatomic tract tracing and functional neuroimaging studies find that the majority of the cerebellum forms connections with "cognitive" association cortices, not with motor areas (Buckner et al., 2011). Thus, just as the cerebellum receives efference copies from the motor cortex, it may also receive cognitive plans from higher-order areas, allowing for cognitively-driven sensory attenuation (Ito, 2008; Sokolov et al., 2017). One striking example of this is the placebo effect, which shows that cognitive predictions arising from external verbal suggestions, contextual cues, and prior experiences can modulate our sensory perceptions of pain. Manipulating participants' anticipated pain by leading them to believe that they are receiving pain-modulating treatment (even when they are not), can attenuate their subsequent perceptions of pain intensity. As in Kilteni and Ehrsson (2020), increased connectivity between the cerebellum and somatosensory network has been associated with reduced pain perception (Kong et al., 2013), and predictions of pain intensity modulate cerebellar activation (Kong et al., 2006). Cerebellar predictive mechanisms may, therefore, be important for optimization of our sensory experience, be it driven by internal movement or external events.

Predictions inform more than just our sensory perception of the world around us. Our beliefs about the world are constantly challenged and refined by incoming perceptual, social, and linguistic information (Kube and Rozenkrantz, 2020). For example, our experiences and beliefs inform predictions of social dynamics, which allow for rapid detection of deviations in our interactions and lead to better adaptive social behavior. Difficulties in these types of predictive abilities have been linked to challenges in the sensory and social adaptive behaviors that characterize autism spectrum disorders (Sinha et al., 2014). Crucially, in autism, the cerebellum is one of the most consistent sites of abnormality, and cerebellar differences are associated with symptom severity in both sociolinguistic and sensorimotor domains (D'Mello and Stoodley, 2015). Moreover, predictive abilities across multiple cognitive domains have been associated with activation in cerebellar regions overlapping with those reported by Kilteni and Ehrsson (2020) (e.g., Moberget et al., 2014; Van Overwalle et al., 2014; D'Mello et al., 2020). These findings together with those of Kilteni and Ehrsson (2020) provide support for the potential role of the cerebellum as a hub for domain-general predictive processing. Via connections with multiple cerebral brain regions, the cerebellum may act on information transmitted from the body and/or environment (whether about touch, pain, or social behaviors) to inform predictions across motor, sensory, and cognitive realms.

Future research should determine whether the cerebellum drives expectation-induced perceptual modulation by acting on the cerebellum, whether it contributes to disorders in which predictive processing is implicated, and whether fMRI has the right resolution to capture these processes. Future investigations should also assess whether domain-specific mechanisms differentiate prediction in action from cognition (Yon et al., 2018), and whether the brain enhances or attenuates predictable information in domains outside of action (Press et al., 2020). Regardless, despite contributing to predictive processing across domains, the cerebellum remains an understudied region of the brain in humans. The results of Kilteni and Ehrsson (2020) provide a good starting point to investigate these processes further.

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