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NEUROSCIENCE

When perceptual learning occurs

A study now finds that visual perceptual learning of complex features occurs due to enhancement of later, decision-related stages of visual processing, rather than earlier, visual encoding stages. It is suggested that strengthening of the readout of sensory information between stages may be reinforced by an implicit reward learning mechanism.

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Visual perceptual learning (VPL) is defined as a long-term increase in visual performance as a result of visual experiences[1]. For example, in an X-ray image an experienced radiologist can easily detect a cancer that a non-expert cannot. It has been shown that experience or training can result in improvements in visual abilities not only with young people but also with older individuals[2] and people with amblyopia[3]. However, the neural mechanisms underlying such improvements are not well understood. Clarification of the neural mechanism behind visual and brain plasticity may lead to therapies that ameliorate diseases affecting vision, and other forms of pathological or age-related visual decline. The study by Diaz *et al.* in this issue of *Nature Human Behaviour* reports an intriguing finding that contributes to a better understanding of neural mechanisms of VPL[4].

Visual cortical processing involves many cortical areas with different functions. It takes about 30 milliseconds for visual signals to travel from the retina to the primary visual cortex, where simple visual features are processed. After being processed in the primary visual cortex, the signals go through multiple visual cortical stages. Signals that are processed later tend to represent more complex features or objects. By 50–60 milliseconds after the visual signals hit the retina, goal-oriented decision-making based on these signals occurs. Determining what stage in visual processing is involved in VPL is important because it indicates the type of visual functions that are improved in VPL. However, this has remained a controversial issue: some researchers support the view that VPL results from early changes in the representation of visual features in primary visual cortex[5–7]. By contrast, other researchers have proposed that VPL is not associated with changes in the representation of visual features, but happens during later stages of visual and/or decision-related processing[8–10], for example, by strengthening the readout of sensory information.

Diaz *et al.* addressed the question as to whether perceptual learning in humans occurs due to enhancement in early sensory representations or in later stages of decision-related processing[4]. They used a face versus car categorization task in which subjects were presented with a very blurred picture and were instructed to report whether it was a face or a car. Over three days of training, almost all subjects improved their performance on the task. That is, VPL of classifying faces and cars took place. Brain activity was measured by electroencephalogram (EEG) before, during and after training. Using EEG decoding and a sophisticated computational model to analyse the data, Diaz *et al.* found that the training enhanced the late (decision-related processing) EEG component and that the amplitude of changes were correlated with increased performance. However, no significant change was observed in the early (visual encoding) EEG component. Since the late-phase component generally reflects higher-level decision-related processing in the brain, the authors concluded that VPL results from strengthening of the readout of sensory evidence used for the decision, which may be reinforced by an implicit reward learning mechanism. Although this model has been built and supported by human psychophysics[8] and monkey unit recording studies[9], no clear results of human brain processing using temporally resolved signals existed. The present study provides the first evidence in support of the readout model based on human brain imaging methods.

The study by Diaz *et al.* suggests the importance of the involvement of higher cognitive areas in VPL, possibly by changing connectivity between sensory and decision stages reinforced by reward processing. At the same time, as the authors acknowledge, the results of this study do not disconfirm other models, such as the early-level model and the two-plasticity model. As mentioned above, the early-level model assumes that VPL is due to changes in the representation of the trained feature[5–7]. The two-plasticity model hypothesizes that VPL is associated with changes both in the representation of the feature and in processing related to the trained task and decision-making[1]. Trained features used in VPL are usually very simple and may have a representation in early-visual stages occurring in the primary visual cortex[5–7]. By contrast, in the

present study, much more complex stimuli, such as a face and a car, were trained and a primary representation of these stimuli may have been made in higher cognitive stages. That may be why no significant change was observed in the early (visual encoding) EEG component.

In summary, Diaz *et al.* have provided valuable new understanding of the temporal dynamics of VPL in decision-related processing in humans. Future studies will need to establish common rules that can explain various types of VPL to clearly understand plasticity in the human adult brain.

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