Early visual experience drives precise alignment of cortical networks for binocular vision

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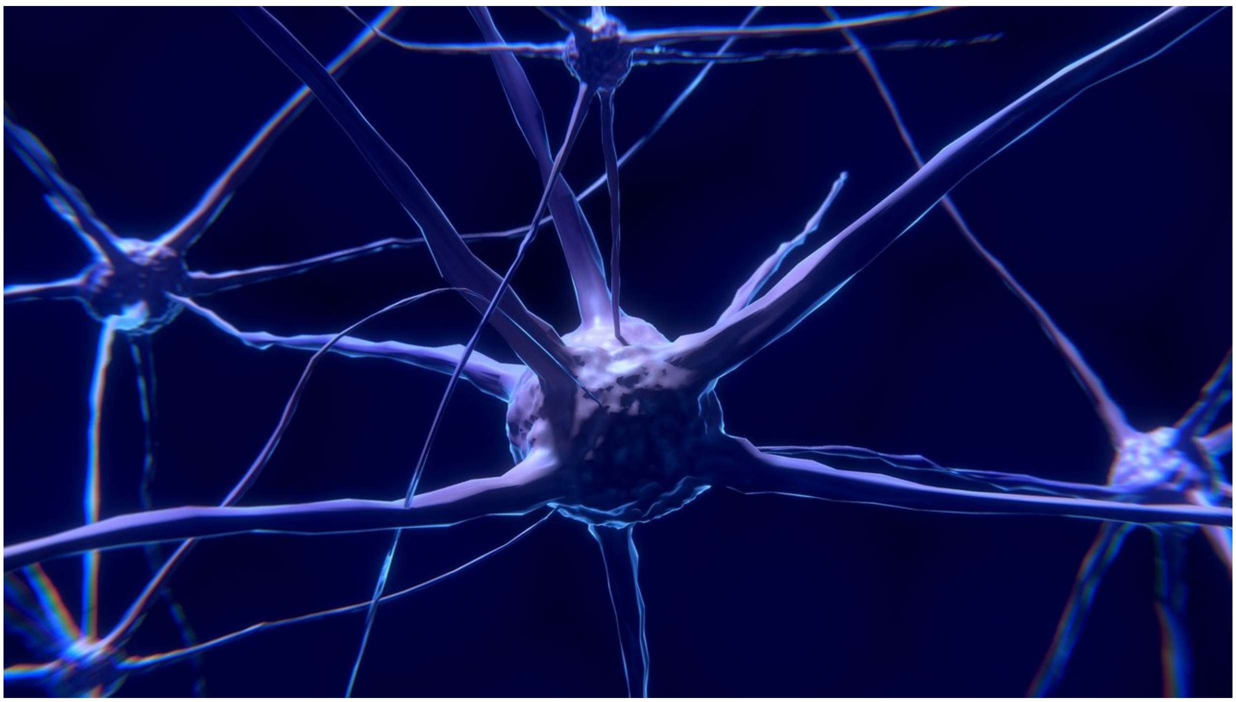

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Neural networks in the visual cortex of the brain do a remarkable job of transforming the patterns of light that fall onto the retina into the vivid sensory experience of sight. A critical element of this encoding process depends on neurons that respond selectively to features in the visual scene. Edges and their orientation in space carry an enormous amount of information about the visual environment, and individual neurons in the visual cortex encode this information by responding selectively to a narrow range of edge orientations; some respond maximally to vertical or horizontal, and others to different orientations in between.

But neurons in visual cortex face another challenge in representing visual information: They must bring together the signals that originate from the left and right eyes to create a single unified binocular representation. The association of the inputs from the two eyes occurs in the visual cortex, and researchers know that this is achieved with a high degree of precision such that individual neurons respond selectively to the same orientation with stimulation of either the left or right eye. What has been missing is a clear understanding of the developmental mechanisms that are responsible for uniting the inputs from the two eyes, a gap in knowledge that led Max Planck Florida researchers to a series of experiments that have revealed a critical role for early visual experience in guiding the formation of a unified binocular representation.

The first issue that Max Planck scientists Jeremy Chang, David Whitney, and David Fitzpatrick wanted to address is whether alignment of the inputs from the two eyes requires visual experience. Does the brain use vision to align the representations? They approached this question in the ferret, a species that has a well-organized visual cortex with a repeating modular structure in which nearby neurons have similar orientation preferences, resulting in distinct patterns of activity across the cortical surface for different orientations. This makes it possible to use imaging techniques that detect calcium signals to visualize the different modular patterns of activity that are associated with different orientations.

Prior to the onset of visual experience, they found that monocular stimulation produced activity patterns that had all the hallmarks of the mature visual cortex except one: the modular patterns of activity produced by stimulation of the left eye with a single orientation were different from the modular patterns produced by the same stimulus orientation presented to the right eye. In other words, brains are capable of developing orderly network representations of edge orientation in the absence of visual experience, but these networks lack the binocular alignment that is seen in mature animals.

Additional experiments allowed the investigators to uncover a dynamic process that occurs over a short period of time (seven to 10 days) in which visual experience drives the alignment of these early representations. Importantly, the researchers found that the period when visual experience is capable of supporting alignment is limited to the first week after eye opening, making it clear that early visual experience is critical for proper development of the circuits that support binocular vision for the rest of life.

These results suggested that binocular visual experience early in development is likely to be a key factor in the alignment of the network representations of the two eyes. This led them to wonder what the patterns of activity in visual cortex would look like for simultaneous stimulation of the two eyes early in development before alignment has been achieved. Surprisingly, they found that binocular stimulation led to the appearance of a third modular representation—one that was distinct from the patterns of activity found for stimulation of the two eyes independently. By tracking these three representations across time, they discovered that the early binocular representation was more stable than the others, appearing most similar to the mature, unified representation that emerges with visual experience. Thus, the activation of this binocular representation with the onset of binocular visual experience may guide the reorganization process, ensuring that all three representations become aligned as a single coherent network.

Ultimately, these changes in network structure must reflect changes in the response properties of single neurons, and to probe the process of alignment at the cellular scale, they turned to experiments using two-photon imaging that allowed them to visualize the response properties of individual neurons. Consistent with the network representation observations, individual neurons exhibited mismatched orientation preferences for monocular stimulation prior to the onset of visual experience that are rectified by changes in preferred orientation induced by visual experience. The next steps of this project are to investigate network reorganization at the synaptic scale, to identify precisely which components of the cortical network are changing and the mechanisms that enable the change.

A greater understanding of the mechanisms responsible for the experience-dependent alignment of cortical networks is critical for addressing visual disorders that arise from early abnormalities in visual experience such as amblyopia. But experience-guided alignment of cortical networks is likely critical for a broad range of brain functions—sensory, motor, and cognitive— that are optimized to support effective navigation and interaction with our world. Identifying those aspects of brain circuitry that depend on early experience for proper alignment, and understanding the underlying alignment mechanisms could offer insights into a host of neurodevelopmental disorders whose causes are still largely unknown.

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