mode to transverse vibrations. This previously unseen vortex motion indicates that an instability accompanies a structural transition to a state in which the vortex centres form a zigzag chain. Compared with the 0.08-THz mode, those at 0.3–0.4 THz are associated with more-intricate vortex dynamics and can be less easily attributed to a particular type of vibration.

To unravel the full picture of vortex dynamics, future work needs to distinguish between inter-vortex motion, intra-vortex motion and vortex bending. Moreover, the longitudinal mode of vibration must be identified. This mode is associated with a sequence of alternating displacements of domain walls (the boundaries between domains) and has remarkable properties that arise from the associated dynamics of surface charges.

In metals, surface charges oscillate at frequencies corresponding to ultraviolet light (about 10^{15} Hz), and the collective oscillations are known as plasmons. Similarly, in a ferroelectric film, the longitudinal mode causes surface charges to oscillate at terahertz frequencies, and the collective oscillations can be thought of as polarization plasmons. In such a film, as in metals, a quantity called the dielectric constant is negative when the frequency of an applied electric field is lower than the plasmon oscillation frequency. Surprisingly, the dielectric constant in the ferroelectric film remains negative as the frequency of the applied field tends to zero, resulting in a negative-capacitance effect[5] — a phenomenon that promises to reduce the power consumption of next-generation nanoscale electronic devices.

The past decade has seen remarkable progress in developing terahertz semiconductor devices, working in the frequency range between radio waves and infrared light. The potential applications of these devices span wireless transmission of vast amounts of data, detection of distant security threats, 6G wireless technology and opportunities for non-invasive medical imaging. Li and colleagues' discovery that polarization vortices in nanoscale ferroelectric films can vibrate at terahertz-level frequencies could help to scale down terahertz devices to the nanoscale and achieve high-speed, high-density data processing driven by electric fields. Such advances might enable the development of terahertz optoelectronics and plasmonics (plasmon-based photonics), ultrafast data exchange and intra-chip communications in emerging computer circuits.

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Neuroscience

A critical period that shapes motor circuits

Laura Sancho & Nicola J. Allen

A mechanism has been found in fruit flies that enables cells called astrocytes to signal to neurons, closing a developmental window during which locomotor behaviour is shaped. **See p.414**

There are times in an organism's development when parts of the forming nervous system are particularly sensitive to changing inputs. Disrupting these critical periods can have lifelong effects on neuronal connectivity and brain function[1]. For example, there is a critical period during childhood for language acquisition[2]. And altered critical periods have been suggested to play a part in neurodevelopmental disorders, including autism spectrum disorder[3] and schizophrenia[4]. Critical periods have been extensively described in the visual system[1], but, until now, there has been less focus on non-sensory systems. Ackerman *et al.*[5] close this gap on page 414. The authors identify a critical period for motor-circuit development in the fruit fly *Drosophila melanogaster*, and establish the cellular and molecular underpinnings of critical-period closure in this system.

During a critical period, neuronal connections can be reshaped in several ways. Ackerman *et al.* mainly address homeostatic plasticity, in which changes occur across an entire neuron — including in the size of structures called dendrites, which receive synaptic connections from other neurons, in synapse numbers and in the strength of electrical impulses transmitted by synapses[6].

First, the authors used a technique called optogenetics to activate or inhibit neuronal activity in two classes of neuron called aCC and RP2 motor neurons. When they silenced the neurons, both the length and volume of the cells' dendrites increased. By contrast, optogenetic activation led to dendritic retraction. These changes occurred only when neuronal activity was manipulated in the 8 hours after larval hatching, and just 15 minutes of manipulation was necessary to see effects.

Next, Ackerman and colleagues asked if the changes in dendrite shape translated into changes in the numbers of excitatory and inhibitory synaptic connections on the aCC and RP2 motor neurons (these synapses activate and inhibit neuronal activity, respectively). Optogenetic silencing of the neurons resulted in a reduction in inhibitory-synapse numbers and an increase in excitatory synapses. Together, the expansion of dendrites and the shift in synapse composition allowed the neurons to rebalance neuronal activity, counteracting the effect of optogenetic silencing. Optogenetic activation of aCC and RP2 neurons led to a decrease in the number of excitatory synapses, but not to an increase in inhibitory synapses, perhaps owing to the limited amount of cell membrane available for the formation of connections after dendrite retraction. Together, this first batch of findings indicates that there is a critical period for homeostatic changes to dendritic structure and synapse number in the developing motor system of *D. melanogaster* (Fig. 1a, b).

What induces these changes? Neurons are often in close contact with cells called astrocytes, which help to regulate synaptic development and maintain brain function[7]. Ackerman *et al.* therefore used genetic engineering to eliminate all astrocytes in their fruit flies. Dendritic remodelling continued beyond eight hours after larval hatching in the mutant flies, but there was no increase in the amount of remodelling that occurred before the eight-hour period had elapsed. These findings indicate that astrocytes regulate the timing of critical-period closure for the aCC/RP2 system, but not the potential for plasticity during this time. This is a key distinction, because it suggests that different

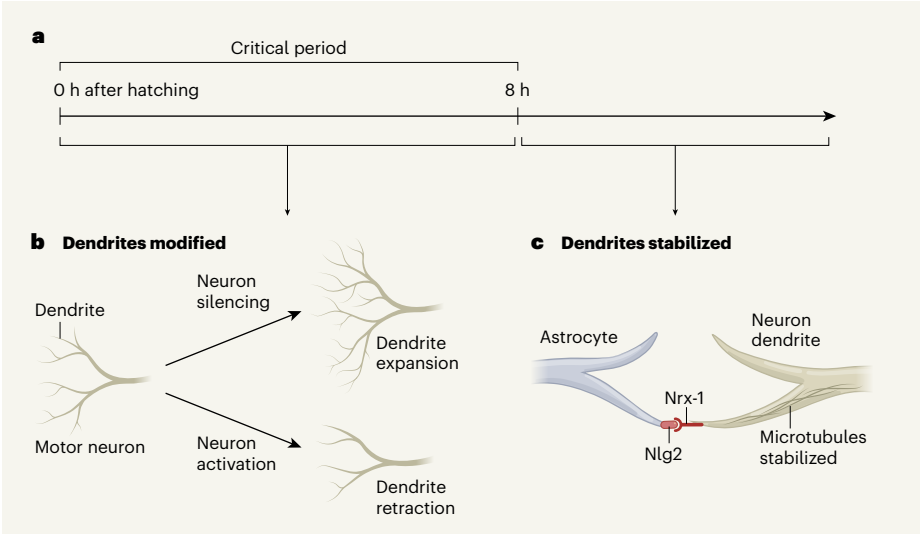

Figure 1 | Shaping a motor circuit. a, Ackerman *et al.*[5] have identified a critical period during which motor circuits involving motor neurons called aCC and RP2 are shaped in the fruit fly *Drosophila melanogaster*. In the eight hours after larval hatching, structures called dendrites, which receive synaptic inputs from other neurons, can be modified, but these dendrites stabilize after the critical period has closed. **b**, Silencing the activity of the neurons during the critical period leads to the expansion of dendrites. By contrast, neuronal activation leads to dendrite retraction. **c**, The critical period closes as neighbouring cells called astrocytes mature. The maturing cells produce the protein Nlg2, which interacts with Nrx-1 protein on the neuronal dendrite. This interaction leads to the stabilization of structures called microtubules, which, in turn, prevents further dendritic remodelling.

mechanisms underlie the two phenomena.

Consequently, Ackerman and colleagues sought to identify the mechanisms involved in the closure of the critical period. They used a technique called an RNA interference screen to inhibit the translation of different messenger RNA molecules into protein in the astrocytes of larvae, and then analysed the time at which the critical period closed in each of the resulting flies. This allowed them to identify genes that might regulate closure of the critical period. There were several genes for which RNA interference led to an extension of the critical period, but in many cases their inhibition also had a profound impact on astrocyte shape, making it hard to dissociate a role in astrocyte development from a specific role in regulating the critical period. The authors chose to focus on the gene *nlg2*, inhibition of which extended the critical period without altering astrocyte shape.

The equivalent gene family in mice, neuroligins, has been linked to astrocyte maturation during the critical period in the visual cortex of the brain, and astrocyte maturation coincides closely with the closure of this critical period[8]. In *D. melanogaster*, Nlg2 protein interacts with the protein neurexin-1 (Nrx-1), which Ackerman and colleagues found to be located in motor neuron dendrites. The authors showed that inhibition of *nrx-1* in aCC and RP2 neurons using RNA interference extended the critical period — thus, Nrx-1 is probably the neuronal receptor for astrocytic Nlg2 in regulation of critical-period closure (Fig. 1c). In line with this idea, overexpressing either *nlg2* in astrocytes or *nrx-1* in aCC/RP2 dendrites closed the critical period prematurely, shortening it to four hours after larval hatching.

Disrupting critical periods can have lasting consequences for neural-circuit function and behaviour. Indeed, Ackerman and co-workers found that extending the critical period (through manipulation of either *nrx-1* or *nlg2*) resulted in abnormal locomotor behaviour, with the larvae moving in abnormal spiralling patterns 1.5 days after the manipulation — a good time period to analyse because, at this stage, the larvae are actively feeding and moving through the culture medium. These alterations in behaviour highlight the importance of proper timing for critical periods.

"The work demonstrates that astrocytes can regulate developmental windows known as critical periods in motor systems."

Ackerman and colleagues' work raises questions for future experiments. For example, how does the interaction between Nlg2 and Nrx-1 regulate the critical period? The current work identified a role for the interaction in stabilizing structural polymers called microtubules, and so in stabilizing the structure of dendrites themselves. However, the mechanism leading to microtubule stability remains to be explored. Furthermore, the dynamics of Nlg2 and Nrx-1 production are still to be determined. Can these proteins be regulated by dendritic retraction or expansion? Would dendritic retraction result from a decrease in *nlg2* expression in astrocytes?

The authors provide compelling evidence for the prominent role of astrocytes in regulating closure of a critical period. Astrocytes regulate aspects of critical-period plasticity in the mammalian visual system[9], including through the actions of the secreted proteins chordin-like 1 (ref. 10) and hevin[11]. The present work demonstrates that astrocytes can regulate critical periods not just in sensory systems, but also in motor systems. Identifying the mechanisms that govern critical-period closure is of particular interest because alterations in closure can disrupt proper neurodevelopment — the findings could therefore lead to insight into mechanisms involved in neurodevelopmental disorders such as schizophrenia[3]. Furthermore, identifying mechanisms of critical-period closure can enable researchers to understand how the brain becomes less plastic in adulthood, providing new avenues for therapeutics aimed at increasing neural plasticity after brain injury or disease.

The work also shows that the role of astrocytes in regulating critical periods extends to invertebrates, thus highlighting the centrality of these cells to nervous system development and maturation. It is becoming apparent that astrocytes and related cell types (collectively called glia) are master regulators of neuronal plasticity, particularly in the context of homeostatic and circuit changes. Moving forwards, research into critical periods must take into account the contribution of glia.

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