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Critical periods shaping the social brain: A perspective from *Drosophila*

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Abstract

Many sensory processing regions of the central brain undergo critical periods of experience-dependent plasticity. During this time ethologically relevant information shapes circuit structure and function. The mechanisms that control critical period timing and duration are poorly understood, and this is of special importance for those later periods of development, which often give rise to complex cognitive functions such as social behavior. Here, we review recent findings in *Drosophila*, an organism that has some unique experimental advantages, and introduce novel views for manipulating plasticity in the post-embryonic brain. Critical periods in larval and young adult flies resemble classic vertebrate models with distinct onset and termination, display clear connections with complex behaviors, and provide opportunities to control the time course of plasticity. These findings may extend our knowledge about mechanisms underlying extension and reopening of critical periods, a concept that has great relevance to many human neurodevelopmental disorders.

KEYWORDS
circuit plasticity, critical period, *Drosophila*, neurodevelopment, sensory experience, social behavior

INTRODUCTION

During critical neurodevelopmental periods, incoming sensory information instructs neuronal circuits to irreversibly rewire for perception and processing of environmental cues. This adapts behavioral responses so as to be appropriate to ethologically relevant stimuli.[1] This is especially true for social behaviors that involve cooperation and complex interactions between individuals. To date, a number of vertebrate model systems have been used to examine CPs,[2–5] but many questions remain. Molecular and circuit mechanisms that control onset, duration and closure of CPs in early postnatal life are still poorly understood. The opportunities for extension and reopening CP in a mature brain require deeper investigation.[6,7] Being able to use this knowledge and manipulate the course and duration of a CP might have an enormous therapeutic potential for a variety of developmental cognitive disabilities, as well as recovery from brain injuries and stroke.[1,8,9] There is a special need to develop new models that specifically address these topics and that provide the ability to control plasticity in the adult brain. In this review we consider the most recent studies focusing on CPs in fruit fly *Drosophila melanogaster* (Figure 1) that provide new insights into regulatory mechanisms, opportunities for in vivo CP manipulations and linking them with maturation of social behaviors. We discuss that *Drosophila* emerges as an integrative neuroethological model of a CP, as it brings together advantages of a simple circuit, sophisticated genetic toolkit and tractable behavior, thereby bridging the gap between the many molecular studies and purely descriptive ethological models. We also suggest possible directions for future studies that could greatly advance our knowledge of CPs.

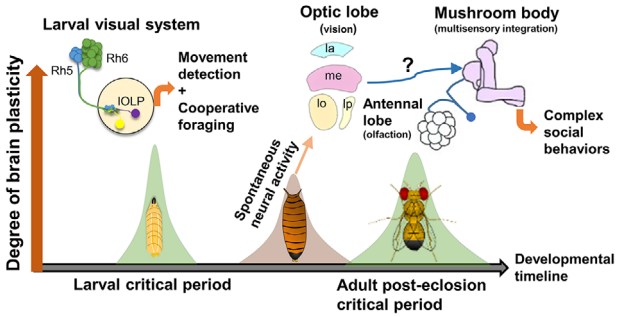

FIGURE 1 Schematic view of neurodevelopmental CPs in *Drosophila*. Similar to that in other animals including humans, the period of intrinsic fly brain sensitivity to social cues is most often limited to short developmental stages and characterized by distinct or gradual onset and termination. During this time, underlying neuronal circuits remain susceptible to structural and functional rearrangements that further lead to proper development of social traits. Mid-larval stage (early third instar) is characterized by sensitivity towards visual-social stimulation and experience-dependent structural and functional plasticity in part the visual system responsible for the emergence of movement detection and cooperative foraging. Spontaneous cell-type specific patterned neuronal activity during later (~48–96 hAPF) pupal stage shapes proper connectivity within developing visual system and other brain regions. Adult fly critical periods are restricted to early post-eclosion stage (1–5 days, in which the first 48 h are the most critical). Sensory input during this time irreversibly shapes structure and function of neurons in antennal and optic lobes (la – lamina, me – medulla, lo – lobula, lp – lobula plate are the neuropils in fly optic lobe) and affects multisensory integration from these and other regions in the mushroom bodies, thereby affecting emergence of complex social behaviors

SOCIAL BEHAVIORS CAN BE REGULATED BY CP PLASTICITY IN SIMPLE CIRCUIT ELEMENTS INVOLVED IN EARLY-STAGE SENSORY PROCESSING

Early post-eclosion, a period that occurs right after pupal hatching, represents a critical stage in insect development. It is important for the regulation of adult behaviors through modulation of underlying circuits' architecture and function. Not surprisingly, all documented CPs inherent to adult fruit fly are restricted to this narrow time frame, including experience-dependent plasticity in primary sensory systems and high-order brain centers (Figure 1).

The *Drosophila* olfactory system is extensively studied in regards to CP-controlled structural and functional plasticity. Relatively simple patterns of circuit connectivity are characterized on morphological and physiological levels and supported by transcriptomics and connectome data.[10–12] Experience-dependent rearrangements are observed already at the first synapse within olfactory glomeruli.[13,14] These are formed between a population of Olfactory Sensory Neurons (OSN) defined by expression of specific odorant receptors and Projection Neurons (PN) that further relay olfactory information to Mushroom Bodies (MB) and Lateral Horn (LH) (Figure 2A).[10–12,15] Behavioral manifestation of olfactory plasticity is seen as long-term habituation (LTH) in response to a specific odorant presentation during but not outside the early (2–3 days) post-eclosion CP.[14,16–18] Cellular substrates for LTH have been identified within both OSNs and PNs. A central role in modulating structural and functional plasticity on both pre- (OSN) and postsynaptic (PN) sites within olfactory glomeruli belongs to a set of multiglomerular inhibitory Local Interneurons (LNs, Figure 2A).[12,14,16] Molecular mechanisms responsible for experience-dependent plasticity within OSN-PN-LN system include cAMP signaling in LNs,[14,16,19] trans-synaptic Notch signaling between OSNs and PNs,[20,21] translational regulation in PNs and LNs,[22,23] as well as pathways downstream of GABA and NMDA receptors (Figure 2A).[13,16,18] Recent studies discussed below have further extended our knowledge about the diversity of local mechanisms that control CP onset and duration.[18,19] These provide new insights into opportunities for in vivo manipulations with these processes, and highlight strong parallels with basic principles of CP regulation in vertebrate models.[1,4] Given the great experimental tractability and its relatively simple structure, fly olfactory system has an enormous potential to serve an integrative model of a CP focusing on both fundamental molecular determinants and long-lasting behavioral consequences of experimental extension and reopening of critical windows.

Sensory input and local inhibitory circuits regulate CP timing

Earlier studies found that exposure of juvenile (2–3 day old) but not older flies to specific odorants induces a reversible volumetric increase in corresponding olfactory glomeruli associated with reduced PN output.[13,14,16,20,22] The latter is a consequence of enhanced sensitivity of iLNs that silence PNs through feedforward inhibition (Figure 2A), leading to PN dendritic elaboration and a subsequent increase in glomerular volume, which is supported by requirement of GABA receptors in PNs for their functional plasticity.[13,16] Therefore, it appears that sensory input from OSNs determines the time frame of CP plasticity mainly through excitatory inputs into iLNs. In addition, recent work demonstrates that CP-restricted odorant exposure is essential for terminal differentiation of OSNs as well.[24] Such requirement for sensory stimulation associated with functional maturation of local inhibitory circuitry resembles that in vertebrate cortex, where local GABAergic interneurons are thought to play a central role in controlling onset and duration of CP plasticity through regulating excitation-inhibition balance.[1,4,25] Glomerular plasticity also relies on NMDA receptors expression in PNs and,[16] most interestingly, in OSNs, where they might display a presynaptic localization.[18] The latter implies an iLN-OSN feedback inhibition serving an alternative mechanism to regulate PN excitability (Figure 2A). Whether both pre- and postsynaptic mechanisms occur synergistically or independently during a post-eclosion CP is yet to be elucidated. However, most experiments were performed independently on individual glomeruli, implying that differences in plasticity mechanisms and CP manifestations could result from unique circuit architecture followed by varying physiological properties of particular glomeruli.[10] In other words, the field has accumulated

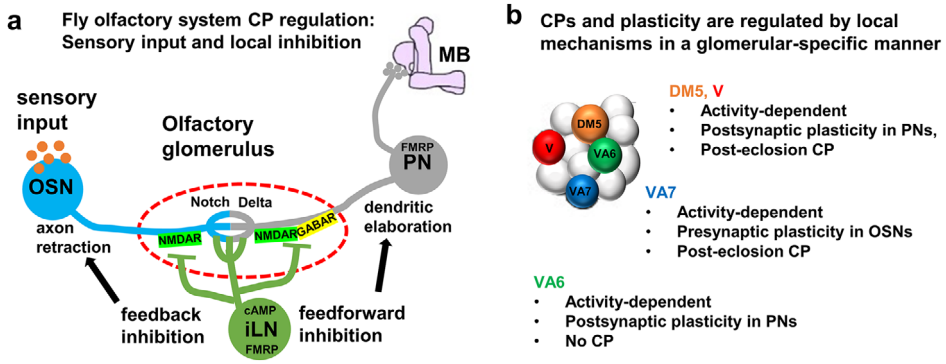

FIGURE 2 (A) CP plasticity in fly olfactory system is regulated by sensory input and local inhibitory circuits. CP plasticity in olfactory glomeruli is induced when olfactory sensory neurons (OSN) are exposed to specific odorants, hence leading to an increased activity of downstream inhibitory local interneurons (iLN) playing a central role in regulation of plasticity. Onset and closure of a CP can be attenuated by silencing of OSNs. iLNs implement GABAR- and NMDAR-dependent feedforward inhibition to silence projection neurons (PN), resulting in PN dendritic elaboration and subsequent increase in glomerular volume, as well as reduction of output level into mushroom bodies (MB). iLNs can also inhibit OSNs through presynaptic NMDAR activity leading to OSN axon retraction. In both cases, local inhibition by iLNs leads to altered OSN-PN connectivity and subsequent olfactory habituation as a behavioral manifestation of experience-dependent plasticity. Some of the molecular mechanisms regulating CP plasticity include cAMP signaling in iLNs, OSN-PN transsynaptic Notch signaling, and FMRP-dependent translational regulation and synaptic remodeling in iLNs and PNs. (B) Plasticity and CPs in *Drosophila* antennal lobe are regulated by local glomerular-specific mechanisms. Experience-dependent structural and functional plasticity in all olfactory glomeruli is driven by exposure to odorants and subsequent activation of corresponding OSNs. This, in turn, triggers alternative glomerular-specific mechanisms of pre- or postsynaptic plasticity driven by enhanced sensitivity of iLNs. While some glomeruli display a CP for experience-dependent rearrangements, others retain plasticity throughout animal's lifetime. The disposition of specified glomeruli serves indicative purposes only and does not correspond to their arrangement in the antennal lobe

evidence of CP plasticity in the fly olfactory system being also regulated in a spatially restricted manner.

Local mechanisms differentially control CPs

A particularly intriguing finding by Chodankar and colleagues (2020) suggests that CP plasticity affecting structure and physiology of neighboring brain regions with similar circuit architecture can be regulated by independent local mechanisms that trigger qualitatively different circuit rearrangements (Figure 2B).[19] Thus, olfactory glomeruli V and DM5 display CP-restricted postsynaptic plasticity in corresponding PNs that requires OSN activity and likely involves subsequent modulation of inhibitory LNs that implement feedforward inhibition of PNs (Figures 2A and B).[19] At the same time, VA6 glomerulus that superficially displays no differences in circuit organization, maintains similar structural and functional plasticity, which is surprisingly not restricted by a CP.[19] This finding opposes a general notion that CP timing is regulated by global mechanisms acting across vast areas of the brain. Instead, it may apply to a small portion of the sensory circuit that encounters a particular stimulus. Moreover, it suggests that the mechanism regulating experience-dependent plasticity and that controlling CPs timing might not be related. This is strengthened by an earlier finding that CP plasticity in VA7 glomerulus does not affect PNs, but involves presynaptic changes in the OSN determined by feedback inhibition from iLNs (Figure 2A and B) and this results in a decrease rather than an increase in glomerular volume.[18] These differences likely arise from variations in glomerular responsiveness to odorant-evoked activity, as well as sensitivity towards modulation by local circuits, which in turn might be determined by distribution of neurotransmitter receptors and other cell surface molecules. This question, as well as its relationship to CP regulation, is very open to experimental investigation.

In vivo control of CP timing has implications for social behaviors

Normal timing of a CP for plasticity in olfactory glomeruli induced by odorant exposure is roughly limited to first 48 h after eclosion, but can be extended in a glomerular-specific fashion upon silencing of individual OSNs, suggesting that sensory input may regulate CP closure.[13,18,19,22] Given that olfactory glomeruli act as autonomous and independently regulated units of plasticity (Figure 2B),[18,19] these results imply that CP duration can be controlled in vivo and without large-scale sensory interventions (e.g. monocular deprivation in vertebrate models).[4] This approach seems especially attractive since CP-restricted modulation of complex behaviors may be operated by both large-scale developmental programs and local glomerular remodeling.[19,26] Previously Kayser and colleagues demonstrated that deficits in courtship behavior may arise from dysfunction of a single VA1v glomerulus, and its plasticity is restricted to an early-life CP.[27] Therefore, activity-controlled manipulation of CP timing in VA1v and other sexually dimorphic glomeruli (DA1, DL3, VL2A) might open a framework for addressing molecular mechanisms underlying maturation of courtship behaviors in the fly.

Manipulation of CP timing in a spatially-restricted manner can find implications for studying human neurodevelopmental disorders. For

example, a fly model of Fragile-X syndrome, a heritable disease associated with Autism spectrum disorders, has revealed a function for FMRP in learning, memory, sleep and social interactions.[8,22,23] The role of FMRP as an activity-sensing synaptic remodeler in PN-KC connectivity refinement has been narrowed down to first post-eclosion days.[22,28,29] In addition, FMRP might itself be involved in the regulation of CP timing through its effect on proper iLN development and subsequent modulation of lateral inhibition in the antennal lobe (Figure 2A).[23] This is supported by an observation that that FMRP-null flies maintain traces of CP-plasticity in maturity.[22] Therefore, extension of olfactory CP by OSN silencing or FMRP downregulation/overexpression will allow to restore CP-restricted synaptic plasticity and observe the effects on social behaviors.

What are the consequences of extending CPs beyond their normal limits? And what are, if any, the downsides of reopening windows for experience-dependent plasticity in the adult brain? An opportunity to manipulate the duration of a CP and see the effects on social behaviors is still elusive. Given the availability of versatile tools to manipulate neuronal activity with a single-cell resolution and time-specific manner, fly olfactory system represents a simple and tractable model for delving deeper into mechanisms that shift, extend or reopen CPs, and allows to correlate resulting circuit changes with alterations in olfaction-guided social behaviors

CP PLASTICITY SPANS OVER FUNCTIONALLY LINKED SENSORY SYSTEMS AND HIGHER ORDER BRAIN REGIONS TO PRODUCE COMPLEX BEHAVIORS

Early studies have documented experience-dependent structural plasticity in *Drosophila* optic lobes, MB calyx and central brain restricted to a post-eclosion CP.[30–32] Light deprivation during this sensitive window resulted in an irreversible volumetric reduction of the corresponding brain regions. Detailed examination revealed that these structural changes resulted from lack of activity-dependent neuropil growth during the first post-eclosion day rather than a gradual decrease in primary volume. In addition, flies reared in the darkness during first post-eclosion days display irreversible visual alterations.[33,34] These observations oppose a general notion about the highly stereotyped and genetically hard-wired connectivity pattern within fly visual system tuned by spontaneous neural activity during later pupal development (Figure 1B).[35–38] Until recently, it remained completely unknown whether observed plasticity reflects qualitative changes in circuit connectivity, mere decrease in fiber density, variations in cell numbers or perhaps a combination thereof.

Toll receptors link CP plasticity with neuronal survival and proliferation

A recent study revealed that Toll-receptor signaling may underlie some aspects of brain plasticity during early post-eclosion CP.[39] Multiple Toll isoforms are implicated in both neuroprotective role and neurodegeneration in the ventral nerve cord, as well as in structural plasticity in the juvenile fly optic lobes, MB and central brain through regulation of cell survival and proliferation.[39] Induction of activity in the optic lobe during first post-eclosion days increases neuronal number via the Toll-dependent pathway suggesting that this mechanism accounted for experience-dependent change in brain volume.[30–32] In accordance with this, overexpression of Toll-2 increased cell number in optic lobes of young adult brains, presumably through de-repression of progenitor cell quiescence and induction of cell cycling.[39] Altered function of Tolls resulted in extensive neuronal death in the optic lobe associated with altered morphology and misrouting of axonal and dendritic processes. This suggests a critical role of Tolls in early development of this brain compartment. Finally, seven out of nine Toll receptors found in *Drosophila* displayed a compartment-specific distribution in the brain, which implies an opportunity to control experience-dependent plasticity in an independent and non-redundant fashion during the CP.[39] These results highlight the role of Toll receptors as major molecular determinants regulating a fine balance between neurodegeneration and plasticity in the brain, but now placing it in the context of early-life CP.[40] Future studies will likely shed more light on specific molecular origins of Toll-mediated CP plasticity, but it is clear that findings by Li and colleagues (2020) may open a larger framework for manipulating components of Toll signaling pathways for experimental restoration of compartment-specific plasticity in mature *fly* brain with potential relevance to vertebrate models.[39] In future, this could elucidate possible consequences of CP extension and reopening and answer whether neurodegeneration represents a toll for unlimited neuronal plasticity

Is multisensory integration during CPs a key for emergence of social behaviors?

Early evidence revealed that MB and central complex are also susceptible to structural rearrangements during early post-eclosion CP.[30,32,41] MB volume and fiber number are affected by light regime, social conditions, and even gender composition throughout days 1-5 post eclosion.[30,32,41] Moreover, negative effect of dark-rearing can in part be leveled by crowding, suggesting that the CP for MB development in newly eclosed flies is associated with multisensory input.[32] This is consistent with the role of MBs as a center for associative learning relying on multimodal integration and consolidation.[42–45] In addition, the function of Toll receptors for CP-dependent MB plasticity was identified.[39] This implies that similar molecular mechanisms may regulate CP developmental plasticity in both primary sensory circuits and higher order brain centers responsible for sensory integration and processing. Recent studies have detailed specific patterns of social interactions between adult flies, revealing that these require consolidation of multimodal inputs including vision, olfaction, gustation and mechanosensation, while early post eclosion social isolation introduced irreversible social deficits.[46–49] These observations combined with earlier findings on social-induced structural plasticity in MBs during a CP suggest a framework for investigating how multisensory

feature integration during early-life shapes higher order brain centers responsible for social behaviors.[30,32,41] Can this knowledge be used to manipulate the timing and duration of plasticity and see whether social behavior may be reprogrammed by reopening a CP in adult brain? If so, future research will likely yield molecular-neuroethological models of how experience instructs the brain to integrate into a social environment through structural and functional circuit rearrangements, principles that can be further extended to mammalian and human models.

CP IN *DROSOPHILA* LARVA: LINKING SOCIALITY WITH A PLASTIC ARCHITECTURE OF A SIMPLE NEURONAL CIRCUIT

While having two orders of magnitude fewer cells than the adult, *Drosophila* larval brain represents a highly tractable model for molecular-neuroethological studies. Full connectome reconstructions are available for multiple larval brain regions including olfactory circuit,[50] visual system and mushroom bodies,[51,52] and several studies have been able to link functional organization of large brain centers with the existing structural data.[53–56] Larvae also display complex behavioral traits including cooperative behaviors, [57–62] many of which that require social learning during a CP.[58,60,63] Thus, *Drosophila* larva is becoming a promising neuroethological model for investigating CP plasticity.

Sensory experience during CP regulates visually-guided social behavior

In crowded conditions and liquified food, third instar larvae form cooperative synchronized digging clusters that persist for several days until animals exit food for pupariation.[57–59] While multiple modalities appear to regulate larval digging and foraging, visual feedback appears to play a key role in larval cooperation.[58,59,64,65] Interestingly, clustering requires both vision and prior social experience in that blind, dark-reared and socially isolated animals similarly fail to coordinate digging efforts efficiently within groups, while initial cluster formation remains unaffected, suggesting that animals rely on olfactory or mechanosensory cues for simple aggregations.[58] Detailed investigation revealed that both social isolation and light deprivation exclusively during a ~24 h period during early third instar (Figure 1) are sufficient to induce irreversible clustering deficits.[58] Therefore, fly larvae display an example of social learning restricted to a short CP, where animals visually interact with peers in order to later acquire social traits for cluster membership. How exactly this process occurs is unknown, but it is possible that young larvae are able to imprint movement patterns of other larvae they are exposed to during the CP in order to further be attracted to it,[63,66] which strikingly resembles classic examples of filial, sexual and food imprinting documented in multiple evolutionary distant animal taxa.[67–69] . This notion is further strengthened by multiple recent evidence of larval simple visual system being capable of detecting movements including ones of other larvae.[54,58,63,70] This example demonstrates that a social behavior may be governed by developmental changes within a simple neuronal circuit, hence making it possible to reduce CP-plasticity down to its mechanistic components and facilitates deciphering of the underlying molecular determinants.

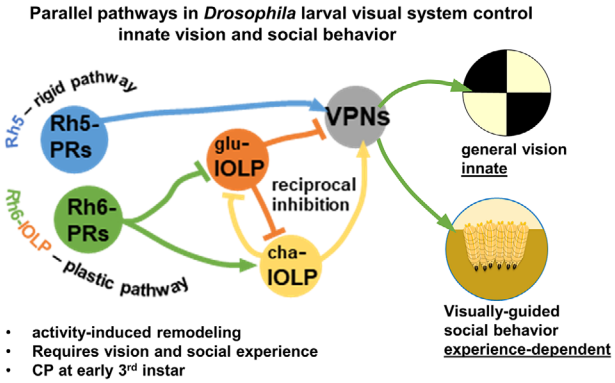

FIGURE 3 Socially induced structural and functional plasticity in *Drosophila* larval visual system regulates visually-guided social behavior. The relatively simple larval visual system includes two parallel pathways. Rh5-photoreceptors (PR) input directly into a set of visual projection neurons (VPN) and regulate general vision (light–dark discrimination). Rh5-PR pathway is hard-wired and does not seem to depend on external sensory experience. A parallel visual pathway originates at Rh6-PRs and includes a pair of local optic lobe pioneer (lOLP) interneurons. Rh6-lOLP pathway acts as a movement-detecting module through ON and OFF selectivity achieved by mutual inhibition of glutamatergic and cholinergic lOLPs. In addition, the Rh6-lOLP pathway controls larval cooperative digging behavior and allows animals to follow movements of immediate neighbors. Visual and social experience during a short CP during early third instar shapes structure and function of Rh6-lOLP pathway and therefore controls maturation of larval social behavior.

A simple and experimentally accessible circuit controls social behavior

Further work established a neuroanatomical connection between social clustering, vision and requirement for CP-restricted experience. Fly larval visual system consists of two parallel pathways with different intrinsic properties (Figure 3). Rh5-PR pathway is responsible for general light-dark discrimination and maintains an extremely rigid structure and function throughout development (Figure 3).[54,60,70] A pathway involving Rh6-PRs and a downstream pair of second-order r lOLP interneurons represents an early-stage movement-detecting module.[54,60,70] Rh6-lOLP pathway specifically regulates social clustering (Figure 3), and serves a cellular substrate for socially induced CP plasticity: light deprivation and social isolation result in significant structural alterations of Rh6 presynaptic boutons, while postsynaptic properties of lOLP neurons are notably reduced in dark-reared and socially isolated animals.[60] These plastic changes are consistent with a CP for emergence of movement detection (Figure 1B):[58,63] dark

rearing or social isolation exclusively during this short period are sufficient to induce irreversible circuit changes and prevent larvae from later engagement into clustering.[60] How exactly Rh6-IOLP socially induced plasticity is regulated on a cellular and molecular levels, and what determines the onset and termination of larval sensitivity to visual experience is currently unknown. The effect of social isolation on structural and functional circuit architecture and resulting complex behaviors has been described in multiple vertebrate models.[71–74] At the same time, a simple Rh6-IOLP pathway represents an easily accessible cellular substrate, and is open to molecular analysis. Combination of approaches uniquely advantageous to *Drosophila* such as high-performance forward genetic screens and molecular techniques such as single-cell transcriptomics targeted at differences between naïve, socialized and social-deprived brains will allow to combine identification of molecules involved in regulation of CP plasticity with its extension and evaluation of consequences for a social behavior.

Long-term consequences of larval sociality may be seen in adult animals

Recent evidence suggests that cooperative foraging in *Drosophila* larvae might be the manifestation of kin selection during preimaginal stage and advantages of group membership are seen in adult animals as increased fitness.[61,62] These results stand in line with a well-established notion that larval density and nutritional status largely affect developmental time,[75] adult body size and fecundity. [76–78] This is consistent with a current view of indirect kin recognition being determined not so much by genetic relatedness as by spatial proximity of the individuals during early life, when exchange of multimodal sensory stimuli imprints recognition patterns into juvenile brains.[79] In this regard a question of even bigger interest is whether sociality acquired during larval CP may have distinct behavioral consequences for adult animals. So far controversial evidence exists regarding the role of larval experience on imaginal behaviors in insects.[80–82] Although a significant part of larval visual system degenerates during metamorphosis, extraretinal eyelet descending directly from larval Rh5-PRs remains functional as a circadian regulator in adult flies and might therefore be implicated in social functions.[83,84] At the same time, CP plasticity originating from larval visual system might be extended to high order centers of larval brain responsible for visual processing and associative learning. Thus, a large portion of MB KCs are either present by the time a CP occurs (γ-KCs born in the embryo and early larva) or appear during late larval stage when animals engage in social behavior ($\alpha'\beta'$-KCs).[85] These could be great candidates for consolidating preimaginal experience and having an impact on adult social performance. Future experiments focused specifically on correlations between larval cooperative foraging and adult social interactions will reveal if *Drosophila* larva can become a unique model system where controlled cell-specific manipulations with individual's CP plasticity can be correlated with long-lasting social deficits.[46,48,86]

CONCLUSIONS AND OUTLOOK: IN SEARCH FOR A TRACTABLE MODEL SYSTEM FOR "SOCIAL" CRITICAL PERIODS

Relationship between ethologically relevant sensory input during early-life CPs and emergence of social behavior is widely established, and effects of social deprivation during CPs have been documented at different levels of organization. However, a model system that covers all of these levels simultaneously is yet to be found. This leads to a growing gap between examples of social behavior shaped by juvenile experience and an opportunity to link these observations with underlying genetic and molecular mechanisms. The field would benefit from a simpler invertebrate model of a plastic social brain. Eusocial insects with their relatively simple nervous systems represent highly attractive models for studying neurological origins of sociality, and examples of primitive early social learning have recently been documented.[87,88] At the same time, lack of genetic accessibility and a challenge to reproduce highly complex hierarchical social structures in laboratory conditions impose significant experimental difficulties. In this regard, a non-eusocial *Drosophila* and in particular its larval stage surprisingly steps in by integrating genetic accessibility with a robust and tractable behavioral phenotype. Social foraging emerging among larval *Drosophila* represents a unique system in that it combines a mechanistic model of social behavior, allows access to and manipulations with the underlying simple neuroanatomical substrate that undergoes structural and functional maturation amid CP social learning, while establishing a causal relationship between manifestation of sociality and its benefits.

CONFLICT OF INTEREST

The authors declare no conflict of interest

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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