

# Connectomic analysis of the central complex in fruit fly larvae



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I would like to dedicate this thesis to my loving parents ...



## **Declaration**

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 60,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

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## **Abstract**

### **Abstract**

In holometabolous insects such as the fruit fly *Drosophila melanogaster*, the brain central complex (CX) develops during metamorphosis and serves the adult stage. Whether a form of the CX exists in the brain of the evolutionarily novel larval stages is not known. Here, we analyzed the connectome of the larval brain and, on the basis of neuronal lineages, synaptic connectivity patterns, and anatomy, identified a putative larval CX, comprising 4 key neuropils: the protocerebral bridge (PB), the ellipsoid body (EB), the fan-shaped body (FB) and the noduli (NO). Consistent with our interpretation, we found in the larval brain synaptic connectivity patterns characteristic of the adult, including (i) visual input into the PB and EB; (ii) modulation of CX neuropil inputs by the mushroom body (MB); (iii) reciprocal connectivity between CX neuropils and select MB compartments; and (iv) strong connectivity between CX neuropils. While some neuronal lineages contributing to the larval CX do not contribute to the adult CX, many others are conserved. The characterization of a larval CX brings structure to largely unexamined larval brain circuits, linking with a vast body of literature, and will inform the design of experiments to probe larval brain function.



# Table of contents

<b>List of figures</b>	<b>xv</b>
<b>List of tables</b>	<b>xvii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Mapping brains - The Power of Connectomics . . . . .	1
1.2 The advantage of the <i>Drosophila</i> larva brain . . . . .	3
1.3 Navigation: Fundamental Across Species . . . . .	4
1.4 The Central Complex . . . . .	5
1.4.1 Central Complex across insects . . . . .	5
1.4.2 Central Complex of Adult <i>Drosophila</i> . . . . .	5
Protocerebral Bridge (PB) . . . . .	6
Ellipsoid Body (EB) . . . . .	6
Fan-Shaped Body (FB) . . . . .	7
Noduli (NO) . . . . .	8
Neuromodulatory neurons in the CX . . . . .	8
Mushroom Body and the CX . . . . .	9
1.5 Larval Central Complex as a research opportunity . . . . .	10
<b>2 Methods</b>	<b>15</b>
2.1 Reconstructing neurons in Electron Microscopy Volumes . . . . .	15
2.1.1 Connectome data . . . . .	15
2.1.2 Neurons Segmentation . . . . .	15
2.1.3 Data Analysis . . . . .	15
2.2 Identification of Central Complex Neuropils . . . . .	16
2.3 Identifying non-Mushroom Body Dopaminergic Neurons . . . . .	16
2.3.1 Multicolor Stochastic Labelling via FLP-out . . . . .	16
2.3.2 Fly Strains . . . . .	16

2.3.3	Immunohistochemistry . . . . .	17
2.3.4	Imaging . . . . .	18
2.3.5	Matching LM images with Seymour Data . . . . .	18
2.4	Loss-of-Function Behavioural Assays . . . . .	18
2.4.1	Fly strains . . . . .	18
2.4.2	Behavioural Experiments . . . . .	18
2.4.3	Behavioural Quantification . . . . .	18
2.4.4	Behavioural Data Analysis . . . . .	19
2.5	$\text{Ca}^{2+}$ Imaging with Light Sheet Microscopy . . . . .	19
2.5.1	Fly lines . . . . .	19
2.5.2	Sample Preparation . . . . .	19
2.5.3	LSM and Functional Imaging . . . . .	19
2.5.4	Data Analysis . . . . .	19
<b>3</b>	<b>Results</b>	<b>21</b>
3.1	Strategy for identifying CX neuropils in the larval brain . . . . .	21
3.1.1	Identifying larval neuronal lineages that contribute to the larval CX	22
3.1.2	Connectivity of CX neurons . . . . .	22
3.2	The Central Complex of <i>Drosophila</i> Larva . . . . .	25
3.2.1	Protocerebral Bridge . . . . .	25
3.2.2	Ellipsoid Body . . . . .	32
3.2.3	Fan-Shaped Body . . . . .	35
3.2.4	Noduli . . . . .	41
3.3	Mushroom Body and the Central Complex . . . . .	41
	A loop between FB and the 'c' compartment of the MB . . . . .	42
	Reciprocal connectivity between EB ring neurons and the 'g' compartment of the MB . . . . .	42
	A loop between the NO and the MB vertical lobe via the LAL . . . . .	44
	The MB modulates inputs to the PB . . . . .	44
3.4	Dopaminergic neurons (DANs) of the larval central complex . . . . .	45
3.5	Behavioral Assays - Loss of Function Analysis during light stimulation . . . . .	48
3.6	Neural activity in response to blue light stimulation . . . . .	49
3.7	Descending Neurons from CX . . . . .	50
<b>4</b>	<b>Discussion</b>	<b>53</b>
4.1	Multisensory integration . . . . .	53
4.2	. . . . .	53

<b>Table of contents</b>	<b>xiii</b>
4.2.1 Navigation, place learning, and memory . . . . .	54
4.2.2 DANs in the FB and PB . . . . .	55
4.2.3 Conclusion . . . . .	56
<b>Appendix A Appendix title example</b>	<b>57</b>
<b>Appendix B example2</b>	<b>59</b>
<b>References</b>	<b>61</b>



# List of figures

3.1	Central Complex Neuron Classes . . . . .	26
3.2	The Central Complex Neuropils in Adult and Larva . . . . .	27
3.3	Larval CX neuron boutons define the volumes of the 4 main CX neuropils .	28
3.4	PB Dalv1 Neurons . . . . .	30
3.5	PB columnar neurons . . . . .	32
3.6	<b>Ellipsoid Body Neurons</b> Ring and Wedge Neurons with their corresponding lineages. The mushroom body is shown in magenta as a landmark in the larval brain. <b>A.</b> Ring neurons of lineage Dalv23, namely RN1/2a and RN1/2b; <b>B.</b> Ring neuron RN3 originating from lineage BAmv1/2; and <b>C.</b> The 8 EB wedge neurons (W1-8) originating from DALcl12 lineage. Panel <b>D.</b> depicts all these neurons stacked together to form the EB . . . . .	33
3.7	<b>EB Neurons Connectivity.</b> Both tables display the connectivity patterns among ring and wedge neurons in the ellipsoid body (EB). Each neuron is separated into left (_l) and right (_r) counterparts to represent lateralization. <b>Upper table:</b> axo-dendritic connections (color-coded in the green spectrum). <b>Lower table:</b> axo-axonic connections (color-coded in the yellow spectrum).	34
3.8	<b>Visual Input into the EB.</b> Input from visual Projection Neurons (Visual PN) to the Ellipsoid Body (EB) via two convergence neurons (CN53, CN54), a pair of PB DALv1s and a second-order Mushroom Body output neuron (MB2ON-187). . . . .	35

3.9 FB tangential cells, also known informally as "horseshoe" neurons for the shape of their bilateral axons. The seven hs-FB subtypes are shown, each with a morphological reconstruction (top) and a simplified schematic (bottom). Input synapses (dendrites) are indicated by blue arrows, and output synapses (axons) by red arrows. The mushroom body is shown in magenta. Neuron counts (left+right) are given below each schematic. <b>A–C.</b> Individual examples of hs-FB.1, hs-FB.2, and hs-FB.3. <b>D.</b> Overlay of hs-FB.1 through .3, illustrating the FB compartments they define. <b>E–H.</b> Individual examples of hs-FB.4 through .7. . . . .	37
3.10 FB Columnar Neurons . . . . .	39
3.11 Noduli Neurons . . . . .	42
3.12 Mushroom Body Connections to the Larval CX . . . . .	43
3.13 Confocal Images of Immunostained Dopaminergic neurons of the Larval Central Complex . . . . .	46
3.14 Loss of Function Analysis during Light Stimulation . . . . .	48
3.15 Lightsheet volume Segmentation . . . . .	50
3.16 Neural Activity of the Larval Brain in response to Photoreceptors Rh5 Stimulation . . . . .	51

# List of tables

1.1	Major Connectomic Datasets . . . . .	2
1.2	<i>Drosophila</i> Adult Central Complex Lineags . . . . .	12
1.3	<i>Drosophila</i> Adult Central Complex Neurons . . . . .	13
3.1	Lineges of the Adult CX that also contribute neurons to the Larval CX . . . . .	23
3.2	Larval Central Complex Lineages . . . . .	24
3.3	Contribution of lineage to CX . . . . .	25
3.4	CX Core Neurons . . . . .	29
3.5	PB horizontal fibers connection to PB columnar . . . . .	30
3.6	Connectivity between FB Tangential and FB Columnar neurons. Cell shading corresponds to relative connection strength (darker = stronger). . . . .	40
3.7	<b>Neurons tested for LOF</b> Neuron names, corresponding split GAL4 line used for LOF experiments, and lineage information. . . . .	49



# Chapter 1

## Introduction

### 1.1 Mapping brains - The Power of Connectomics

Investigating the origins of human behaviour and mapping it to onto the brain is a mission as old natural philosophy. Hippocrates was the first to identify the brain as the 'analyst of the outside world', the interpreter of consciousness and the center of intelligence and willpower [6], and to this day he is considered the forefather of neurology.

At its heart, neuroscience has always been about reverse engineering human behaviour. We attempt to understand the full functionality of the brain from its underlying anatomical features - molecular and cellular - its activity and its circuits. Ultimately, the goal is to infer causality about behaviour using the best tools we have at our disposal [56].

Detailed maps of synaptic connectivity (also known as wiring diagrams) are a core to our understanding of the fundamental link between brain and behaviour and, crucially, how malfunctions of it can result in behavioral or neurological disorders. Whilst large-scale circuit reconstructions aren't yet possible with state-of-the-art imaging technology - the human brain has 86 billion cells[33], with tens of thousands of synapses each, and would take centuries to map - advances in tiny brains mapping are pushing the brain sciences by unraveling causal and correlative relations between structure and function and paving the way to establishing fundamental principles of how neural systems operate.

Connectomics - the study of complete sets of connections in individual neural systems - is at large responsible for a lot of these advancements. It allowed us to create roadmaps for brain of various animals such as the *C. Elegans* - the first landmark study of a connectome [7] -, the mouse visual cortex [23], the *Drosophila* adult [75] as well as the *Drosophila* larva[62, 5, 50, 15, 16, 17]. All these datasets were obtained via a technique known as electron microscopy (EM, ssEM, TEM, FIB-SEM) and have become foundational references in neuroscience, ushering in the long-anticipated era of synaptic wiring diagrams (Table 1.1).

Organism	Tissue / region	Neurons	Imaging method	Project / Reference
<i>C. elegans</i>	Entire CNS	302	ssTEM	White et al. (1986); Witvliet et al. (2021, <i>Nature</i> )
<i>C. intestinalis</i> (larva)	Entire CNS	177	ssTEM	Ryan et al. (2016, <i>eLife</i> 16962)
<i>P. dumerilii</i> (larva)	Entire CNS	9 162	ssTEM	Veraszto et al. (2024, <i>eLife</i> 97964)
<i>D. melanogaster</i> (larva)	Entire CNS	~9 700	ssTEM	Winding et al. (2023, <i>Science</i> )
<i>D. melanogaster</i> (adult)	Entire brain	~135 000	ssTEM	Zheng et al. (2018, <i>eLife</i> 16962; <i>Cell</i> )
<i>M. musculus</i>	Visual cortex (VISp + HVAs)	~100 M (per mm <sup>3</sup> )	SBF/MB-EM	MICRONS v3 ( <i>Nature</i> , 2025)

**Table 1.1 Fully-mapped Connectomic Datasets** Comparison of major connectomic datasets across species, from *C. elegans* to mouse visual cortex. All values are directly reported in the cited publications; no extrapolated voxel or volume data are included. Abbreviations: ssTEM, serial-section transmission EM; SBF/MB-EM, serial block-face or multi-beam EM.

EM is, to this day, the highest-resolution technology for brain mapping, allowing us to visualize the smallest neurites (as small as 15 nm; [57]) and all the synaptic connections—vesicles and clefts (40 nm and 20 nm, respectively)—between them. The great advantage of tiny animal models such as *Drosophila* is that their physical dimensions ( 600  $\mu\text{m}$  or 0.15  $\text{mm}^3$  for the adult fly brain; 242  $\mu\text{m}$  or 0.001  $\text{mm}^3$  for the larval nervous system) can be reconstructed with synaptic resolution within a manageable timeframe and cost. Their dimensions - no neuropil greatly exceeds 50  $\mu\text{m}$  in depth [57] — also facilitate the use of multimodal imaging approaches: confocal microscopy for molecular and genetic labeling, light-sheet microscopy for rapid volumetric imaging (sometimes paired with calcium activity), and electron microscopy for ultrastructural detail—on the same specimen or across comparable samples.

The female adult vinegar fly *Drosophila Melanogaster* is one of the largest pieces of nervous tissue collected and imaged by EM (i.e., FAFB; [97]). The dataset encompasses 40 teravoxels and 21 million serial section transmission EM images, covering a  $995 \times 537 \times 283 \mu\text{m}$  volume at  $4 \times 4 \times 40 \text{ nm}$  resolution. Complementary to this, a complete EM reconstruction of the *Drosophila* larva central nervous system ([93]) spans the entire brain and ventral nerve cord within a roughly 242  $\mu\text{m}$  volume, capturing approximately 9,700 neurons at  $3.8 \times 3.8 \times 50 \text{ nm}$  resolution. I have contributed to mapping the larval fruit fly, specifically, in unraveling a new area responsible for navigational decisions. This area is known as the Central Complex in the adult, and, as I will go on to show, I postulate that an analogous, numerically smaller Central Complex exists at the larval stage of development.

Together, these datasets bridge developmental stages of the fly nervous system, enabling both sparse and dense connectomic analyses that inform a growing range of hypotheses around their relevance to function and behaviour. Collectively, connectomic datasets provide a structural framework through which brain function can be interpreted. They transform anatomy into networks and reveal not only which neurons are connected but also the direction

of information flow. This is the exact type of data that is translatable into connectivity matrices — quantitative maps of presynaptic and postsynaptic partnerships— that we can therefore use we can infer circuit logic and predict functional pathways to expose hidden motifs, highlight convergence or divergence across modalities, and delineates subnetworks anatomical areas that underlie specific behaviours. Using *Drosophila* is powerful approach to functionally study these detailed wiring diagram, because it is one of the most experimentally accessible animal model.

## 1.2 The advantage of the *Drosophila* larva brain

Historically, for connectomes of larger insects of vertebrates, connectomes of isolated areas have been studied and made sense of. However, brain regions don't operate in isolation and connectivity inside the whole brain spans multiple dispersed areas, neurons can converge or diverge towards each other, and understanding any single computation requires understanding its inputs, outputs and relation to other regions of the brain [36]. Functional (Ca activity) studies confirm this to be the case in *Drosophila* [51]as well as in vertebrates [1].

A smaller circuit is therefore advantageous for its accessibility to assess dispersed neural computations. With its nervous system comprising 12 000 neurons and only 2,500 of these inside the brain - all of which have been mapped with synaptic resolution using whole-CNS EM, and its brain networks mostly reconstructed - the fruit fly larva is especially well suited for brain-wide circuit studies. This animal's circuit architecture is stable across larval stages (1st, 2nd and 3rd instar) with neurons only growing in size but not changing synaptic partners [25]. In addition, the larva vinegar fly has rich but numerically limited adaptive behaviour that is equivalent from 1st to 3rd instar [3].This means that behaviour observed in later stages(which can be a favourable choice as they are more easily identified by cameras and generally easier to work with ) can be mapped onto our circuits from the 1st instar.. Brain structures homologous to adult and other insect species ([15, 89, 9])

Not only does the larval fly have a full synaptic-resolution connectome, this animal has a vast library of genetic driver lines (GAL4, LexA) for targeted gene expression in individual neurons, as well as effector line (UAS, LexOp), which allows for controlled expression of proteins that allow (e.g.) optogenetic manipulation via CsChrimson [45] or monitoring neural activity via GCaMP7 [65].

Our ability to genetically manipulate protein expression in individual neurons and record their activity in freely behaving larvae, as well as quantify simple output behaviours [91], link them directly to their circuit and infer from adult structures, makes it a very tractable

option to identify specialised, functionally distinct natural networks from our reconstructed larval circuits.

### 1.3 Navigation: Fundamental Across Species

When one wants to inspect connectivity maps to understand universal principles of neural computations, one must start with the fundamentals and ask themselves: what are some aspects of the brain that are universally true across species?

Certainly what is true for all species is they need to find resources, shelter and avoid threats by navigating their environment. Navigation is therefore a fundamental and crucial function of biological systems across the board.

Navigation is achieved via multisensory integration, a process wherein sensory cues are integrated into one coherent neural representation, to maximize sensitivity and reduce ambiguity. Interpreting sensory inputs requires dynamic transformations that allow the brain to ignore transient sensory distractions and compensate for fluctuation in the quality of information or its temporal availability. Once sensory inputs are processed, they're followed by action selection via activation of specific muscles.

During navigation, the brain is able to retain a model of the world (i.e. neural representations of the external world persist) in absence of sensory input. This relies on attractor dynamics generated by referral neural circuits in the deep brain regions rather than at the sensory/motor periphery.

Deep-brain circuits' inputs and outputs are usually difficult to identify and characterize, especially those involved in flexible navigation whose circuits have large populations of neurons. Importantly, deep-layer connectivity is nearly impossible to determine in large brain animals, such as mammals. For this reason, smaller animals, such as insects are best suited for such studies, with their numerically smaller, tractable neural circuits, they provide the opportunity to obtain a detailed understanding of deep-layer computations underlying navigation.

Insects are expert navigators. They maintain a specific pattern of action selection over many minutes and even hours during behaviors like foraging or migration, and maintain a prolonged state of inaction during quiet wakefulness or sleep (Hendricks et al., 2000; Shaw et al., 2000). These behaviors are initiated and modulated based on environmental conditions (for example, humidity, heat, and the availability of food, nutritive state, hunger, hydration etc) and an insect's internal needs (such as sleep drive and nutritive state; Griffith, 2013). The context-dependent initiation and control of many such behaviors has been shown to depend on a conserved insect brain region called the central complex (also known as CX)

## 1.4 The Central Complex

*Parts of this section incorporate text from published work [The central complex of the larval fruit fly brain] (Lungu et al., 2025)*

### 1.4.1 Central Complex across insects

The Central Complex (CX) is a conserved set of neuropils found across arthropods (bumblebee, the red flour beetle, Monarch butterfly) that acts as a sensory integration area and a center for coordinated motor activity [68, 90, 30].

Ancestrally, the central complex arises during embryogenesis in hemimetabolous insects - insects that undergo ‘incomplete’ metamorphosis, whose nymph stages transition slowly over multiple steps into the adult shape, with their brain developing gradually(e.g. beetle or cicada). Later derived holometabolous insects - those that compress all nymph stages into a sessile stage(the pupa) - undergo ‘complete metamorphosis’, and have distinct larval, pupal and adult stages designed to restrict developmental resources to those needed for growth. In this case, the central complex arises during postembryonic stages (e.g. flies, moths, bee).

This brain region originated more than 400 million years ago and has remained highly conserved across insect species, comprising 4 neuropils: the protocerebral bridge (PB), the ellipsoid body (EB; or central body lower unit/CBL), the fan-shaped body (FB; or central body upper unit), and a pair of noduli (NO). The CX is known for its stereotypical regular neuroarchitecture composed of vertical columns(columnar neurons) and horizontal layers (tangential neurons). Columnar neurons link the PB with the other CX neuropils (EB,FB,NO) forming columnar compartments in each of them. Tangential cells input horizontally across the entire surface of a neuropil, and intersect with columnar neurons [35].

### 1.4.2 Central Complex of Adult *Drosophila*

In the fruit fly, the central complex starts forming during late larval and metamorphic stages, via the proliferation of pioneer undifferentiated neurons that remain quiescent until the pupal stage. This is in contrast to other holometabolous insects such as the tribolium [18] whose CX cells begin arborizing during embryogenesis.

In *Drosophila melanogaster*, the functions of the CX include multi-sensory navigation, path integration, place learning, allocentric orientation of the head relative to its body, sleep regulation, and providing an internal sense of direction in the absence of stimuli, among others [28, 61, 78, 68, 83, 22, 32, 85, 70, 81, 20].

At the adult stage, the fruit fly CX has four well-studied neuropils: the Protocerebral Bridge (PB), the Fan-shaped Body (FB), the Ellipsoid body (EB) and the Noduli (NO) [28] plus, as of recently, the Asymmetrical Body (AB) [95], in addition to several smaller accessory neuropils often referred to as the lateral complex: the gall (GA), the lateral accessory lobe (LAL) - which is interconnected with all other neuropils - and the bulbs (BU) [94, 22, 38].

The Central Complex neuropils originate primarily from DM lineages (DM1-DM6) in addition to neuropil specific ones (Table 1.2) [96, 4]. The DM1–DM4 lineages generate the small-field columnar neurons that innervate all the four major CX neuropil (PB, FB, EB, NO) in highly ordered isomorphic patterns to establish projections across different CX compartments. Other lineages are more specialised, such as DM5 which exclusively innervates the PB, or DL1 which only innervates the FB.

### **Protocerebral Bridge (PB)**

In the adult *Drosophila*, the PB comprises two sets of bilaterally symmetric compartments, sometimes referred to as glomeruli 1–9 [38], positioned at the most posterior-dorsal location possible in the brain.

These compartments are arranged in a continuous manner medio-laterally, contacting at the midline. In the adult, about 600 neurons innervate the PB, organized into hundreds of types ( 194 [94], see Table 1.3) that are split into two main general groups: the columnar neurons (from lineages DM1, DM2, DM3, DM4 and DM6) whose dendrites innervate one or more of the 9 + 9 compartments of the PB [94]; and the horizontal neurons (also known as horizontal fibers) derived from a single lineage (PBp1; [4]) whose axons innervate many or all PB compartments.

In the adult, the PB receives visual input via relay neurons (POL neurons) conveying information on polarized light, in a highly structured pattern across its compartments that binarizes the continuum of angles of polarized light ([31]). Then the PB relays this information to the EB compartments (Fig.).

In addition to visual input, the adult PB also integrates olfactory inputs [38], suggesting that spatial navigation is not unimodal but integrative across multiple sensory modalities.

### **Ellipsoid Body (EB)**

The adult Ellipsoid Body (EB) is a ring-shaped structure situated between the Fan-Shaped Body (FB) and the Mushroom Body horizontal lobes, facing anterodorsally. The EB is made of two main types of neurons: Ring-neurons (RNs; derived mainly from the EBAa1/DALv2

and LALv1/BAmv1/2 lineages) that spread their axons across the length of the EB, and reciprocally connected Wedge neurons (EPGs, derived from the DM4 lineage) that divide the EB into 16 compartments (the wedges) [94]. The EPG (Wedge) neurons are excitatory and synapse with each other, as well as reciprocally with the Ring neurons, which are inhibitory [22, 38].

The adult EB circuit has been modeled as a ring attractor [83] to, in concordance with its anatomy, reproduce *in silico* the observed "bump" of neural activity in the form of a sole active wedge in the *Drosophila* adult EB [79].

EPG (Wedge) neurons form 16 wedges around this ring, and project to both hemispheres of the PB, where they connect to two sets of columnar neurons (PEG and PEN) that project back to the EB, forming recurrent loops. The anatomical offset between EPG and PEN neurons is key to how the fly head direction system translates angular motion into an updated position of the activity bump in the ring attractor [83].

In the adult, the EB receives visual inhibitory GABAergic inputs, via two parallel pathways for distinct visual information: 1. Ring neurons that map the visual environment of the fly; 2. tangential neurons that take in information about body rotations and translational velocity. The latter receive input in the LAL and output to the NO.

Mechanosensory input also enters the CX via the second-order projection neurons to the EB. These neurons code head direction; some proprioceptive input has also been observed [38]. It receives strong inputs from PB, NO and the LAL, and outputs onto the PB.

### Fan-Shaped Body (FB)

The adult FB is a bilaterally symmetric neuropil posterior and dorsal to the EB, with well-defined horizontal and vertical components: 6 horizontal layers stacked dorso-ventrally that are defined by distinct sets of horizontal neurons (FB tangential neurons); and 9 vertical columns stacked medio-laterally are defined by column-specific columnar neurons. Both horizontal and vertical neurons innervate the FB in a layer- and column-restricted manner [29]. As the biggest CX neuropils, a large variety of lineages contribute to the FB (see Table ??). In the adult FB there are 2 types of FB tangential cells: (1) neurons that relay the presence of an attractive odor to the FB, originating in the MB or the LH (learnt or innate valences; [38]); (2) neurons that relay sleep drive to the FB, whose activity is mandatory for sleep initiation [81].

The adult FB columnar neurons, or columnar input cells, are known as PFN (PB-FB-NO; [95]), with dendrites in the PB and axonic outputs on both the FB and NO. There are 5 main types [38], with their arbors tiling the PB glomeruli, the FB layers, and the NO layers.

The third class of adult FB cells are interneurons with dendrites and axons within the FB. Of these there are 2 main types: FB intrinsic neurons whose arbors lay entirely within the FB, and FB mixed arborisation neurons with additional axonic branches outside the CX and sometimes dendritic branches in the PB [94].

A key feature of the the adult FB is strong innervation by MB Output Neurons (MBONs) [75, 38]. In addition, the axons of dopaminergic neurons driven by visual inputs innervate the FB [53].

### **Noduli (NO)**

The noduli are small, bilaterally symmetric spherical neuropils located medially and ventrally to the FB. In the adult *Drosophila* brain, each hemilateral neuropil is divided in 3 subunits: nodulus 1, 2 and 3 (NO1, NO2, NO3), with NO1 having the highest synaptic density of the three. There are notable variations across insect species, with the number of noduli ranging from two to four per brain hemisphere. While the stacked noduli subunits have been referred to as horizontal layers, no vertical subdivisions have been reported for these structures. Therefore no columnar organization is known.

The NO neurons present a unique morphology featuring compact, clutched axons, which set them apart from other CX neurons [95, 38] and greatly ease their identification even in the absence of the typical conspicuous anatomical neuropil region present in adult insects. In the adult fruit fly, these neurons primarily originate in the DM1, DM2 and DM3 lineages [4].

In the adult *Drosophila* brain, the NO is interconnected with the EB and the FB, with the latter relaying information to the NO from tangential input neurons via several PB columnar cells such as PEN-neurons (PB-EB-NO; from the head direction system) and PFN-neurons (PB-FB-NO) [94, 38]. The primary NO inputs outside of the CX are from the LAL; these are known as LNO neurons and are suggested to be inhibitory [95, 38]. LNOs send inputs to and receive feedback from columnar neurons. FB tangential neurons make weak reciprocal connections to LNOs and columnar neurons in the NO. All columnar neurons (PFNs and PENs) that synapse onto NO (are NO.b) are recurrently connected to the same LNO (LAL-NO) neurons they receive input from.

### **Neuromodulatory neurons in the CX**

In the adult CX numerous neurons express neuromodulators and neuropeptides, and their receptors, particularly in the FB [41, 42]. These modulatory molecules have been associated with the overall level of motor activity and the regulation of sleep [11], among other roles [68].

Here, we list the subset of neurons with assigned neuromodulators that are monosynaptically connected to CX neurons in the larval brain.

The sVUM2mx and sVUM2md are a pair of octopaminergic ventral unpaired medial (VUM) neurons with somas in the SEZ and bilaterally symmetric arbors, which innervate the larval optic neuropil (LON; [50]). These octopaminergic neurons further project their axons into the LAL and also deliver axonic boutons to the EB.

Another octopaminergic VUM (a ladder neuron), named MB2IN-191 [17], innervates the FB bilaterally but not exclusively, with its bilateral axon extending further into nearby medial and posterior areas of the brain.

Given the known role of octopamine in controlling sleep/wake in larvae [85] and the role of the adult CX in modulating motor activity levels and sleep [68, 81], these octopaminergic neurons should be tested experimentally for their potential in mediating a signal for sleep in larvae.

Furthermore, the pair of SP2-1 serotonergic neurons described for the optic lobes [50] present ipsilateral dendrites that integrate inputs from multiple PB.b neurons and also FB.b (hs-FB.6), and then project their axons contralaterally, extending across the PB and into the optic lobe, dropping presynaptic connections onto PB.d neurons and then further posterior and lateral until reaching the LON. These neurons are ideally suited for relaying feedback signals onto the optic lobe to modulate the processing of incoming visual inputs as a function of PB and FB activity.

Another serotonergic neuron, CSD [5], that integrates inputs from olfactory sensory neurons (ORNs) and the superior lateral protocerebrum (an extended area around the LH), and projects back to the antennal lobe (AL) to modulate olfactory LN function [92], integrates strong inputs from the FB intrinsic neuron MB2ON-125.

Taken together, via SP2-1 and CSD neurons the output of the FB may modulate with serotonin both the LON and the AL, presumably to provide context to first-order circuits for sensory processing (vision and olfaction), as has been reported for hunger versus satiation [92].

## Mushroom Body and the CX

In the adult **Drosophila**, the Mushroom Body is known to output onto the Central Complex neuropils through the MB Output Neurons (MBONs). At this stage, adult MBONs primarily target the Fan-shaped Body - tangential neurons from the middle layers (4-6) - and the Noduli - via a direct glutamatergic connection from MBON-30 to LCNOp(LAL–NO) neurons which then target the PFN (PB-FB-NO) neurons [38].

## 1.5 Larval Central Complex as a research opportunity

What is special about the holometabolous insects such as *Drosophila* is the extremely arrested brain development during larval stages [4]. This suggests that other larval neurons must take over essential navigational functions performed by the adult central complex, in the form of what we expect to be an earlier stage larval central complex.

In *Drosophila melanogaster*, the functions of the CX include multi-sensory navigation, path integration, place learning, allocentric orientation of the head relative to its body, sleep regulation, and providing an internal sense of direction in the absence of stimuli, among others [28, 61, 78, 68, 83, 22, 32, 85, 70, 81, 20].

The fruit fly larva exhibits a range of behaviors that require spatial navigation, including chemotaxis for foraging and escape [21, 44, 13, 10] and aversive phototaxis in response to blue light [74, 26, 43]. In addition to responding to an isolated unimodal stimulus, the larva integrates competing stimuli prior to decision making for navigation [24]. Furthermore, larvae sleep, which is required for long-term memory [71] just like in the adult fly [12, 11], where sleep is regulated by the central complex [81].

Anatomically, the larval central brain shares the set of neuroblasts with the adult [48], and presents neuropil areas that directly correspond to those of the adult brain such as the Antennal Lobe (AL), the Mushroom Body (MB), and the Lateral Accessory Lobe (LAL), in addition to more larval-specific neuropils such as the larval optic neuropil (LON) [66]. The organization and synaptic connectivity of the larval AL, MB, and LON are well understood at present [5, 15, 50].

Nevertheless, these neuropils constitute only  $\sim$ 30% of the complete larval brain connectome by number of neurons [93]. We postulate that amongst the remaining  $\sim$ 70% of brain neurons, and given the reported conservation of neuroblasts [48] and neuronal identities from larval to adult [89], and the larval behaviors in navigation and sleep that in the adult are associated with the CX, the question of whether the larval brain harbors a simpler yet homologous set of Central Complex neuropils must be examined. Furthermore, in other holometabolous insect orders, neuroblast proliferation arrests at a later point in the stereotyped sequence of neuron types [88], generating more neurons embryonically and rendering the central complex identifiable at the larval stage, such as in the beetle *Tribolium castaneum* where the CX develops embryonically [46, 19]. In the fruit fly larva, hundreds of late embryonic-born neurons known to later on pioneer the development of the adult CX remain undifferentiated throughout larval life [4].

The larval brain, though, does not present fused brain hemispheres like in the adult. With adult CX neuropils being largely medial structures, any putative larval brain counterparts will differ significantly by morphology alone. The basis of our search for the larval CX has

to rely on (1) neuronal lineages generated by the same neuroblasts; (2) the relative spatial location of neurons within the overall neuropil since these are conserved for neuropils known to be homologous such as the AL, MB, LON and LAL; (3) the synaptic circuit architecture organizing the adult central complex neuropils; and (4) the patterns of sensory inputs. For (1) we use embryonic-born neurons that remain identifiable yet undifferentiated throughout larval life, a subset of which will develop into the adult CX [4]. For (2), (3) and (4) we rely on the fully reconstructed neuronal arbors constituent of the complete connectome of the larval brain [93], together with prior publications on larval sensory systems [55, 62, 5, 76, 50, 59, 37, 34]. We use all four in an iterative process to progressively discover the complete list of neurons composing the putative larval CX.

This thesis aims to identify the putative central complex neuropils of the *Drosophila* larva, characterize their connectivity pathways, neurotransmitter identity, and functional role in behavior, and place these findings in the context of central complex evolution and developmental diversity. To achieve this, I combined connectomic reconstructions, genetic tools, functional imaging, and behavioral assays. The thesis is structured as follows: Chapter 2 describes the analytical and experimental methods used across the study, Chapter 3 presents the main results in the context of specific research questions, and Chapter 4 discusses the implications of these results for our understanding the structure and function of a central complex at an earlier developmental stage of a holometabolous insect.

<b>Neuropil</b>	<b>Lineage</b>
<b>Protocerebral Bridge</b>	DM1 (DPMm1) DM2 (DPMpm1) DM3 (DPMpm2) DM4 (CM4) DM5 (CM5) DM6 (CM3) PBp1 (-)
<b>Ellipsoid Body</b>	DM1 (DPMm1) DM2 (DPMpm1) DM3 (DPMpm2) DM4 (CM4) DM6 (CM3) EBa1 (DALv2) LALv1 (BAMv1)
<b>Fan-Shaped Body</b>	DM1 (DPMm1) DM2 (DPMpm1) DM3 (DPMpm2) DM4 (CM4) DM6 (CM3) DL1 (CP2) EBa1 (DALv2) LALv1 (BAMv1) AOTUv4 CREa1 (BAMd1) CREa2 (DALCm1) SMPad2 (DAMd2/3) SIPp1 (DPMpl2)
<b>Noduli</b>	DM1 (DPMm1) DM2 (DPMpm1) DM3 (DPMpm2) DM4 (CM4) LALv1 (BAMv1) DM6 (CM6) SMPad2 (DAMd2/3)

Table 1.2 *Drosophila* Adult Central Complex Lineags. Individual Central Complex neuropils and their contributing lineages in the nomenclature of ItoLee[49] and (Hertenstein)[54]

Hulse et al Name	Wolff/Francoville Name
<b>EB</b>	
<i>Ring Neurons</i>	
ER 1–6	BU.s EB.b
<i>Extrinsic Ring Neurons</i>	
ExR1–8 (Extrinsic Ring)	NO/BU/LAL/GA.s EB.b
<i>Wedge Neurons</i>	
EPGt (EB–PB Columnar)	EB.s PB.b GA-t.b
EPG (EB–PB Columnar)	EB.s PB.b GA.b
EL (EB Columnar)	EB.s GAs.s.b
WL–L	Wedge–LAL.s.b
<b>PB</b>	
PEN (EB–PB Columnar)	PB.s EB.b NO.b
PEG (EB–PB Columnar)	PB.s EB.b GA.b
PFN (PB–FB Columnar)	PB.s FB.b NO.b
PFR (PB–FB Columnar)	PB.s FBd.b ROB.b
PFG (PB–FB Columnar)	PB.s FB.s.b GA.b
PFL1–3 (PB–FB Output)	PB.s FB.s LAL.b CRE.b
Delta 7 (PB Intrinsic)	PB.s.b
P–ECG	PB.s EB.b GA.b
P1–9 (Octopaminergic)	PB.s EB.b GA.b
LPsP (Dopaminergic)	PB.b LAL.s PS.s
Sps–P	PB.b SPS.s
IbSpsP	PB.b IB.s.SPS.s
P6–8P9 (intrinsic)	PB.s.b
<b>FB</b>	
vDelta (Intra–FB Columnar)	FB.s.b
hDelta (Intra–FB Columnar)	FB.s.b
FR (FX Columnar)	FB.s ROB.b
FS (FX Columnar)	FB.s SNP.b
FC (FX Columnar)	FB.s CRE.b
FB Tangential (FBt)	FB.s (..)
<b>NO</b>	
LNO–1 (LG–N/GLNO)	LAL.s GA.s NO.b
LNO–2 (LNA)	LAL.s NO.b
LNO–3 (LCNOp/LCNOp)	LAL.s CRE.s NO.b

Table 1.3 *Drosophila* Adult Central Complex Neurons This table contains CX neurons nomenclature according to Hulse et.al [38] mapped onto Wolff et al[95] and Francoville [22] nomenclatures which contain information about the location of input regions (.s for dendritic spines) and output regions (.b for axonal boutons)



# Chapter 2

## Methods

*Parts of this section incorporate text from published work [The central complex of the larval fruit fly brain] (Lungu et al., 2025)*

### 2.1 Reconstructing neurons in Electron Microscopy Volumes

#### 2.1.1 Connectome data

The connectome of a 2-hour old first instar larval brain was used, as reconstructed previously by us [93]. The neuronal reconstructions, synapse labels, and neuron annotations, together with the electron microscopy volume, is available at the VirtualFlyBrain

#### 2.1.2 Neurons Segmentation

Neurons were manually segmented using CATMAID

#### 2.1.3 Data Analysis

Data was analysed via the web-based CATMAID software [77, 73], specifically

Results were exported as readable tables mapping neuropil-level connectivity and graph measures. For each neuropil we report: total incoming synapses, total outgoing synapses, in/out-strength, degree, betweenness, eigenvector centrality, clustering coefficient, and assigned community. Tabular outputs were produced as CSV and as LaTeX tables for inclusion in the manuscript and Supplementary Materials. Code and raw matrices used to generate the tables are provided in the project repository to ensure reproducibility.

## 2.2 Identification of Central Complex Neuropils

## 2.3 Identifying non-Mushroom Body Dopaminergic Neurons

### 2.3.1 Multicolor Stochastic Labelling via FLP-out

We were interested if any of the identified central complex neurons are dopaminergic. To verify that, we used the GAL4/UAS system to tag all the dopaminergic neurons(DANs) in the brain, and focused on those located outside the Mushroom Body (non-MB DANs).

We used the MCFO approach to label dopaminergic neurons inside the brain of *drosophila* larva. To do this we used the TH-GAL4 driver line, which expresses GAL4 in dopaminergic neurons. The GAL4 gene is inserted under the control of the tyrosine hydroxylase (TH) promoter, which is specific to DANs, so it's expressed in TH+ (dopaminergic) neurons.

To achieve stochastic multicolor labeling of individual neurons, we used the Multicolor FlpOut (MCFO) system, which relies on FLP recombinase-mediated excision of FRT-flanked transcriptional stop cassettes placed upstream of multiple fluorescent reporter genes. FLP recombinase expression was driven under UAS control and activated by tissue-specific GAL4 drivers. Upon FLP expression, recombination at FRT sites excises stop cassettes in a random subset of cells, allowing expression of distinct fluorescent proteins from a single transgenic construct. This results in combinatorial multicolor labeling of individual cells, enabling detailed morphological analysis. Our line had three MCFO reporters(smGFPs) HA, FLAG, V5.

### 2.3.2 Fly Strains

We used TH-GAL4, a line that tags all dopaminergic neurons in the central nervous system of the larva [80], and crossed it with tsh-GAL80 to suppress expression in the VNC. The following driver line was used: R57C10-FlpL in su(Hw)attP8;; pJFRC210-10XUAS-FRT>STOP>FRT-myrt::smGFP-OLLAS in attP2. pJFRC210-10XUAS-FRT>STOP>FRT.... The following effector line was used: w; tsh-Gal80/cyo.Tb.RFP; TH-Gal4. These were crossed, and the desired progeny was: R57C10-FlpL / + ; tsh-Gal80 / CyO.Tb.RFP ; TH-Gal4 / UAS-smGFP. To select for larvae that express GAL4 only in the brain, only larvae with red fluorescent bodies were dissected, as this indicates the presence of tsh-GAL80.

### 2.3.3 Immunohistochemistry

For Immunohistochemistry, we adapted the protocol from HHMI Janelia Research Campus, in combination with the protocol from [60]. The following primary antibodies were used: **Mouse  $\alpha$ -Neuroglan; Rabbit  $\alpha$ -HA Tag; Rat  $\alpha$ -FLAG Tag** (Sigma). The following secondary antibodies were used: AF488 Donkey  $\alpha$ -Mouse; DL549 Goat  $\alpha$ -Rabbit (Sigma). The following conjugated antibody was used: AF647 Mouse  $\alpha$ -V5

Optimization of the protocol required extensive iteration over many months, during which multiple combinations of primary, secondary, and conjugated antibodies were systematically tested. The aim was to obtain strong, specific signals in all imaging channels without cross-reactivity or bleed-through. The final antibody set reported here represents the outcome of this process and was selected because it consistently provided clear labeling across epitopes, enabling reliable multichannel visualization.

The larval central nervous system (CNS) was dissected in cold 1× phosphate-buffered saline (PBS). The tissue was then transferred into 2 mL Protein LoBind tubes containing cold 4% paraformaldehyde (PFA) in 1× PBS, and incubated for 1 h at room temperature (RT) while nutating. The PFA was then removed and tissues were washed in 1.75 mL of 1% PBT (PBS with 0.3% Triton X-100) four times for 15 min each with nutation. Samples were then blocked with 5% Normal Donkey Serum (NDS Jackson Immuno Research; prepared as 95  $\mu$ L PBT + 5  $\mu$ L NDS), and incubated for 2 h at RT on a rotator with tubes upright. Primary antibody incubation was carried out in 1% PBT (typically 100  $\mu$ L per tube) for 4 h at RT, followed by two consecutive overnights at 4°C with continuous rotation. After primary incubation, tissues were washed four times in 1.75 mL of 1% PBT for 15 min each.

Secondary antibody incubation was performed in 1% PBT (100  $\mu$ L per tube) for 4 h at RT, followed by 1–2 overnights at 4°C with continuous rotation. Post-secondary washes were performed four times in 1.75 mL of 1% PBT for 15 min each. An additional blocking step with 5% Normal Mouse Serum (NMS; Jackson ImmunoResearch, #015-000-120) in PBT was carried out for 1.5 h at RT prior to overnight incubation with at 4°C with the conjugated antibody. Following incubation, samples were washed four times in 1.75 mL of 1% PBT for 15 min each.

For mounting, tissues were placed on poly-L-lysine (PLL)-coated coverslips. Samples were dehydrated through a graded ethanol series (30%, 50%, 75%, 95%, and three changes of 100%), soaking for 10 min at each step. Tissues were cleared by immersion in three sequential 5 min xylene baths. Finally, samples were embedded by applying 4–5 (80  $\mu$ l) drops of dibutyl phthalate in xylene (DPX) to the mounted tissue, placing the coverslip (DPX side down) onto a prepared slide with spacers, and applying gentle pressure to seat the coverslip. Slides were left to dry in the hood for 1–2 days prior to imaging.

### 2.3.4 Imaging

For imaging, the Zeiss LSM 780 was used.

### 2.3.5 Matching LM images with Seymour Data

## 2.4 Loss-of-Function Behavioural Assays

### 2.4.1 Fly strains

The following effector lines were used: UAS-impTNT-HA, UAS-TNT-HA, obtained from the Bloomington Stock Center (Indiana, USA).

We used the following split-GAL4 GMR driver lines: SS01978, SS26146, SS2856, SS22965, SS04497, SS25740, SS27197, SS36847, SS55970 (HHMI Janelia Research Campus; [52, 58]). See Fig. ??.

### 2.4.2 Behavioural Experiments

9 split GAL4 lines were used and crossed with either UAS-TNT (effector) or UAS-impTNT (control) genetic driver lines lines. The cross was set at 25°C and the flies were laid on fly food for 3 days. Larvae containing the UAS-TNT or UAS-impTNT transgene were raised at 18°C for 7 days with normal cornmeal food. Third instar larvae were used for all experiments.

Larvae were separated from food by using 15% sucrose and washed with water, then dried and placed in the center of the arena, consisting in 3% Bacto agar gel in a 25 × 25 cm square plastic plate. Experiments were conducted at 25°C. Larvae were monitored with the Multi-Worm Tracker (MWT) software (<http://sourceforge.net/projects/mwt>); [63].

For light-stimulation experiments, we used approximately 30 larvae for each run. The larvae were presented with green light for 40 seconds, and the amount of larvae turning was monitored before, during and after stimulus presentation. 6 runs were performed for every line.

### 2.4.3 Behavioural Quantification

Larvae were tracked in real-time using the MWT software. We rejected objects that were tracked for less than 5 seconds or moved less than one body length of the larva. For each larva MWT returns a contour, spine and centre of mass as a function of time. Raw videos are never stored. From the MWT tracking data we computed the key parameters of larval motion, using specific choreography (part of the MWT software package) variables<sup>28</sup>. From

the tracking data, we detected and quantified crawling and rolling events and the speed of peristaltic crawling strides.

#### 2.4.4 Behavioural Data Analysis

### 2.5 $\text{Ca}^{2+}$ Imaging with Light Sheet Microscopy

#### 2.5.1 Fly lines

#### 2.5.2 Sample Preparation

Fly larvae were raised on standard cornmeal-based food. Second instar larvae were selected for live imaging. Individual larvae were dissected in physiological saline. After being pinned dorsal side up in Sylgard-lined Petri dishes, a dorsal incision was made along the larval body with fine scissors. The body wall was pinned flat and internal organs were removed. The isolated Drosophila CNS was then dissected away, preserving the Rh5 photoreceptors which expressed fluorescence. Only CNS samples that expressed *irfp* were selected. The samples were then embedded in 1% low-melting temperature agarose in physiological saline at 36 °C. The agarose containing the CNS was drawn into a glass capillary with 1.4 mm inner diameter and 2.0 mm outer diameter, where the agarose quickly cooled to room temperature, forming a soft gel. The agarose cylinder was extruded from the capillary so that the CNS was optically accessible outside of the glass.

#### 2.5.3 LSM and Functional Imaging

The SiMView software was used to locate the brain. There are 2 views, one from the back and from the front. The view was set to an angle that is as flat and central as possible. Imaging is with green (561nm) exciting jRGECO(present in the cytosol) which is the Ca reporter expressed pan neuronally, and with red is the IRFP(expresssd in the nuclei) brightens the cell nuclei very well which allows you to see the cell position.

#### 2.5.4 Data Analysis



# Chapter 3

## Results

*Parts of this section incorporate text from published work [The central complex of the larval fruit fly brain] (Lungu et al., 2025)*

### 3.1 Strategy for identifying CX neuropils in the larval brain

I used an iterative strategy in finding putative larval central complex neurons. For this, I pattern matched individual cells based on adult CX neurons lineages, morphology, relative location and connectivity. Since the adult brain presents fused hemispheres at the midline whereas the larva has not, we placed more emphasis of searching for circuit motifs rather than anatomical similarity, since the larval brain has a brain commissure, while preserving the relative spatial location of a CX neuropil as a constraint.

These included:

1. Integration of sensory inputs: we searched for synaptic pathways corresponding to the adult's for integrating visual inputs into the PB and EB [38], and gustatory inputs into the FB.
2. Association between centers for memory and spatial navigation: we looked for the characteristic link between the MB, the center for associative memory, and CX neuropils, which includes synapses from MBONs (MB output neurons) to the FB, EB and NO in the adult fly.
3. Recurrent intra-CX connectivity, such as with columnar neurons relating the PB with the FB and EB, or with the NO.

### 3.1.1 Identifying larval neuronal lineages that contribute to the larval CX

The *Drosophila melanogaster* central brain consists of stereotyped neural lineages, developmental-structural units of macrocircuitry formed by the sibling neurons of single progenitor cells, the neuroblasts [82], a subset of which structures the CX [67]. Starting with the currently identified set of quiescent, embryonic-born neurons present in the larval brain that develop into the adult CX during metamorphosis [4] we identified larval brain neurons satisfying imposed connectivity rules as per known circuit patterns across the adult CX neuropils [94, 95, 22, 38].

We broadened the search beyond these lineages based on the expectation that some larval neurons may have been recruited to CX structures but would later take another identity in the adult, as is known for larval MB neurons [89], on the basis of matching synaptic connectivity patterns as observed in the adult; for example, for EB Ring neurons we looked for neurons with recurrent axo-axonic synapses with each other and with Wedge neurons, where their axon is located at the most anterior end of the brain neuropil, at an intermediate dorso-ventral position just anterior to the MB medial lobe. We expected to find neurons originating from DM1, DM2, DM3, DM4, DM5 and DM6 hemilineages as these are core lineages contributing to all neuropils (Table 1.2), with the second priority being neuropil specific lineages (e.g. EBa1(DALv2) for the EB see 1.2). 12 of the 15 lineages found to contribute CX neurons in the adult also exist in the larva. Of these, we found that 9 of them contribute neurons to the larval central complex (Table 3.1). We therefore used these 9 lineages as a starting point to find our putative CX neuropils in the larva.

In addition to the lineages that contribute to the adult CX, there were several neurons from other lineages, which satisfied other criteria (such as connectivity patterns or relative location) and were therefore classified as central complex neurons. These lineages are presented in Table 3.2 which contains all the lineages we found to contribute neurons to the larval CX. None of these lineages are exclusive contributors to the larval CX - i.e all of these lineages contribute neurons to other parts of the brain - however, there are a few (about 10) that contribute more than a fifth (20%) of their neurons to CX neuropils (Figure (3.3)).

### 3.1.2 Connectivity of CX neurons

To be able to identify which neurons could contribute to the CX, we investigated their connectivity patterns. Specifically, we summarised where a neuron receives synaptic input (location of its dendrites) and sends output processes (location of its axons). The central complex is known primarily for visual input processing, therefore in the larva we were looking

Adult lineage	Larval lineage
DM1	DPMm1
DM2	DPMpm1
DM3	DPMpm2
DM4	CM4
DM5/DM6	CM1/3
DL1	CP23
EBa1	DALv2
LALv1	BAMv1
CREa1	BAmd1
CREa2	DALCm12
SMPad2	DAMd2/3
SIPp1	DPMpl12

**Table 3.1 Lineages of the Adult CX that also contribute neurons to the Larval CX** Adult CX lineages are listed in the first column, and their corresponding larval lineages in the second.

at neurons downstream of photoreceptors. We investigated cells immediately connected to visual projection neurons (vPNs) which are directly connected to photoreceptors. Several of these neurons have been catalogued as Protocerebral Bridge (see section 3.2.1) or Noduli(see section 3.2.4) neurons. In additon to visual input, we find that olfactory input is integrated by all the larval CX neuropils indirectly via the Lateral Horn(LH) and the Mushroom Body through convergence neurons(CNs; which integrate learnt valences from the MB and innate valences from the LH [16]) or MB output neurons and MB input neurons. This is in line with previous findings about the CX being integrative across multiple sensory modalities [38]. Since Gepner et al., 2015 demonstrated that Larvae have to integrate visual and olfactory gradients, with convergence of these sensory systems before decision to act on themwe expected there would be a structure recieving input from these modalities and used information such as lineage membership to figure out if these could be central complex neurons.

Columnar and horizontal neurons have stereotyped connectivity patterns within the CX, being connected between themselves or with other accessory structures (e.g.LAL). To be able to define these, we categorised them similarly to how they have been categorised in the literature. For naming, we adapted Wolff et al., 2015 nomenclature, and named them on the basis of the location of input synapses (.d for dendrites) and the location of their output synapses (.b for axonal bouttons). Once the synapses for each neuron was mapped, we categorised them on the basis of their location within the CX neuropils and relative to accesory structures as per Figure 3.1. As such we devided them into Intrinsic Neurons(those

Larval lineages	PB.b	PB.d	FB.b	FB.d	EB.b	EB.d	NO.b	NO.d	Total
BAla12				2	2				4
BAla34			4					9	13
BAlp_ant		2			2			1	5
bamd1						1		2	3
bamd2_d			1						1
bamd2_v			3					4	7
bamv12_dor	1			1			2	5	9
BAmv12_dor	1			1			2	5	9
Bamv12_ven	1			1	2	2		1	7
BLAd-OL	2								2
BLAI				2					2
BLAV12_ant				2					2
BLP12						2			2
BLVp2		2							2
CM13_lat		2				4	2		8
CM13_med					2	2			4
CM4-vm				2				4	6
CPa			1						1
CPb					8	4			12
CPe				2				4	6
Dalcl12					16	22			38
Dalcml2-m						4		2	6
DALcm12-v		2		2			4	1	9
dall1		2	4						6
Dalv1	8			6					14
Dalv23					14			4	18
dplal1-3			2		3				5
dplc_post_med		4		2			4		10
DPLc5		6	1	2			3		12
DPMI_ant	3	2						3	8
DPMI12		3		2			2		7
DPMI34_post				1			1		2
DPMm1	4		14	2			4		24
DPMm2		3		2		2			7
DPMpl12		5	2	2					9
dpmpl3								1	1
DPMpm1			4	2		4			10
DPMpm2						2	2		4
Total	20	33	36	36	53	47	24	46	295

**Table 3.2 Larval Central Complex Lineages.** A full list of Larval CX lineages is shown in the first column. If a lineage also contributes to the adult CX, the corresponding adult nomenclature [14] is shown in the second column. Columns 3–6 indicate the number of neurons from each lineage that contribute axons (“.b” for boutons) or dendrites (“.d”) to individual neuropils: PB, FB, EB and NO.

Lineage	Left Hemisphere	Right Hemisphere	CX neurons	CX % of Lineage
Dalcl12	25	27	38	73.08%
Dalv1	11	11	14	63.64%
dplc_post_med	6	10	10	62.50%
DPMl12	13	2	7	46.67%
Dalv23	18	21	18	46.15%
DPLc5	13	14	12	44.44%
dplal1-3	2	12	5	35.71%
CPb	14	20	12	35.29%
DPMm1	38	47	24	28.24%
dall1	9	18	6	22.22%

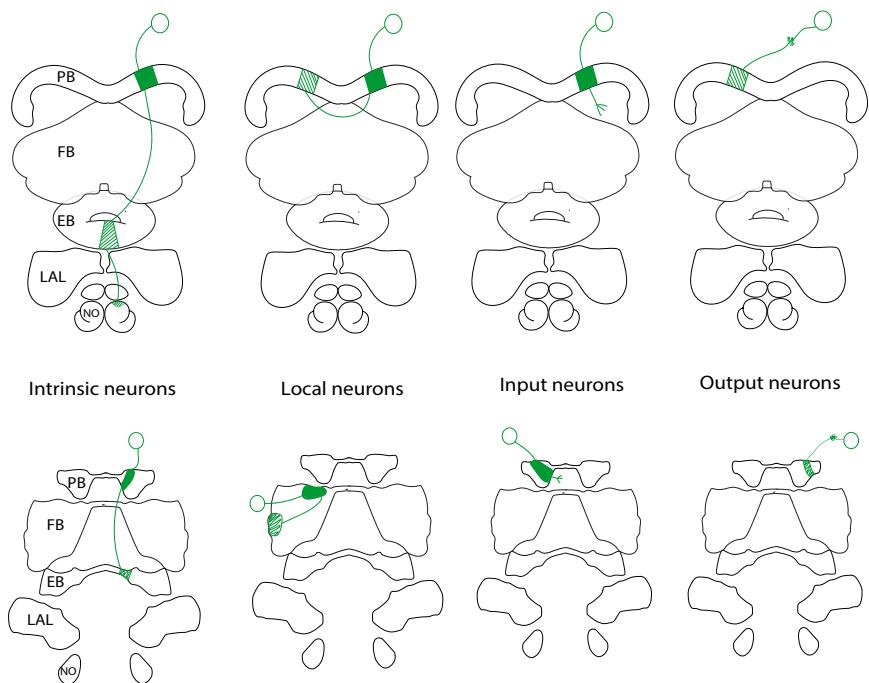
Table 3.3 **Lineage contribution to CX** This table illustrates lineages that contribute more than 20% of their neurons of the CX. the second and third column show their distribution across the brain hemispheres, whilst the last column shows the percentage of neurons that contribute(axons, dendrites or both) to CX neuropils

whose inputs and outputs are located within CX neuropils), Local Neurons (cells whose inputs and outputs located within the same neuropil), Input Neurons (those that send only dendrites processes within the CX and output outside of it) and Output Neurons: Cells that send denritic inputs outside of the CX but output onto the CX neuropils. Since the CX of the larva is numerically reduced, we grouped Intrinsic and Local neurons, and named these **Core CX neurons** for a more concise, cohesive analysis of the CX network. There are 15 pairs of CX core neurons, all of which are presented in Table 3.4. For a comprehensive understanding of the connectivity patterns of these neurons, they have been written in a nomenclature adapted from Wolff et al., 2015 [94]. We classified neurons using the suffixes ".b" (axon boutons) and ".d" (dendrites) for CX neuropils. Hence, a neuron annotated as NO.b projects its axon into the NO, and likewise, a neuron annotated as FB.d places its dendrites in the FB. As such, neurons that are both .b and .d for CX neuropils are the CX Core neurons.

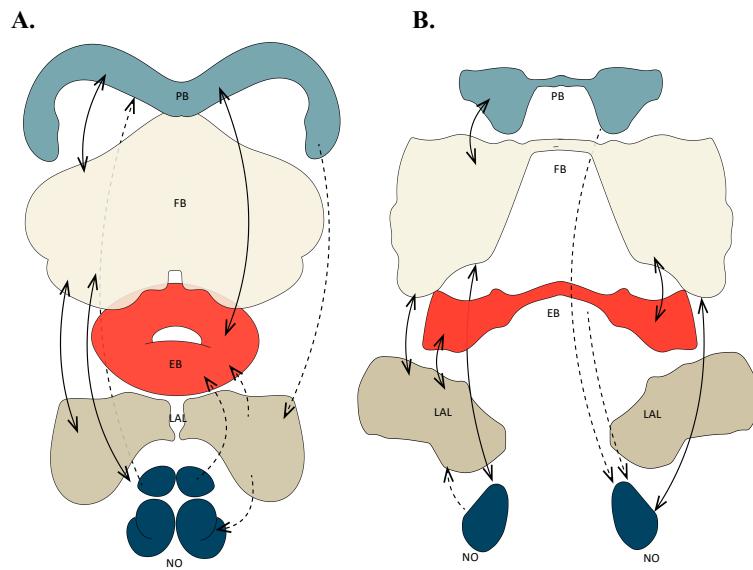
## 3.2 The Central Complex of *Drosophila* Larva

### 3.2.1 Protocerebral Bridge

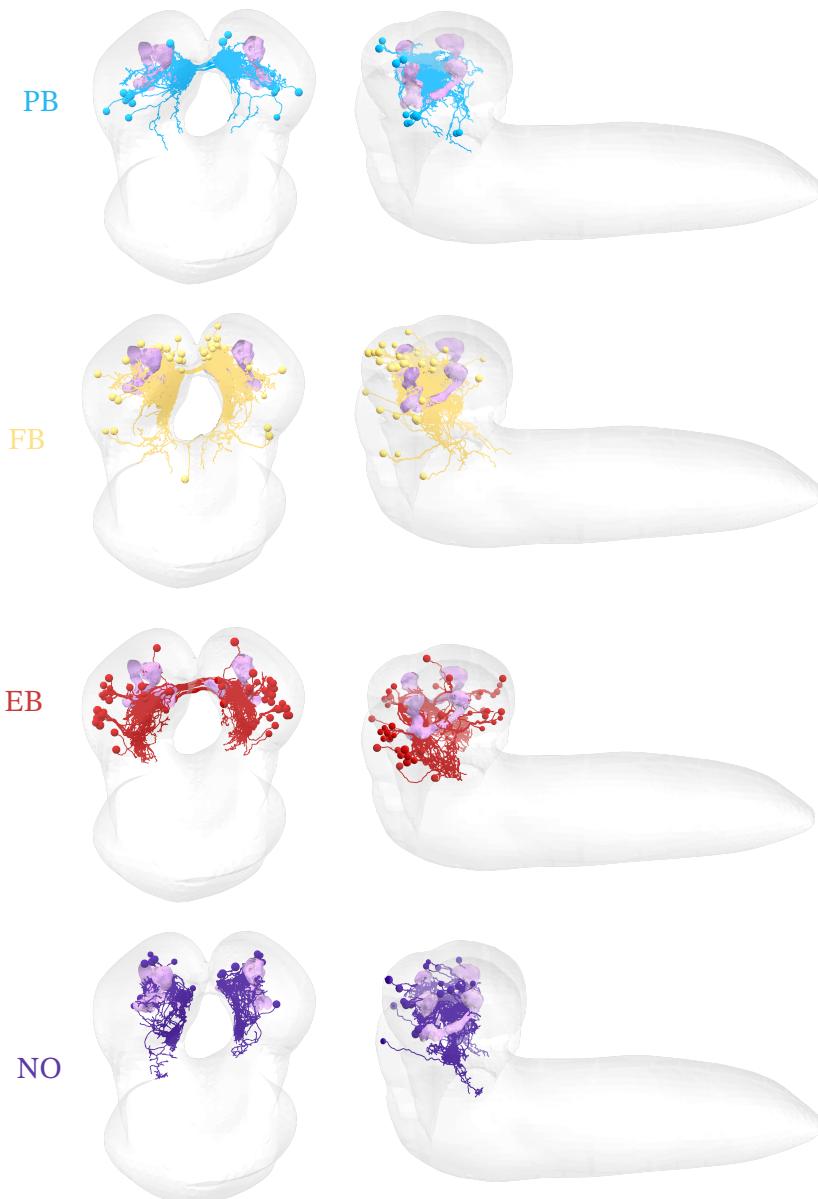
In searching for the larval PB, we expected two sets of neurons: columnar and horizontal. In larva, four central complex lineages contribute columnar neurons, a subset of which position their dendrites at a posterior-dorsal location. We could not find a central complex lineage that would contribute horizontal fibers at a posterior-dorsal location necessary to



**Fig. 3.1 Classes of CX neurons** This schematic illustrates neuron classes of the adult CX (upper panel) and the larval CX (lower panel). The PB, FB, EB, NO and LAL are shown in each case to illustrate where a neuron arborizes. Neurons are drawn as a sketch, where the soma is represented by a green circle, the arbors are split into dendritic inputs - filled green boxed - and spiny axonal outputs - hashed scribbled green boxes. Cells are classified as either **Intrinsic Neurons**:neurons whose inputs and outputs are located within CX neuropils; **Local Neurons**: cells whose inputs and outputs located within one neuropil; **Input Neurons**: Neurons that have dendrites (receive synaptic input) located within the CX but output outside of it; and **Output Neurons**: Cells that receive inputs outside of the CX but output onto CX neuropils



**Fig. 3.2 The Central Complex Neuropils in Adult and Larva.** Dotted-line arrows represent unidirectional connections, filled-line arrows indicate bidirectional connections. In panel A. we show the adult *Drosophila* CX. Bidirectional connectivity is seen between PB-FB, PB-EB, FB-LAL and FB-NO, with unidirectional connections from NO-PB, PB-LAL, LAL-NO and NO-EB; Panel B. displays the larval *Drosophila* CX. Bidirectional connections are PB-FB, FB-EB, FB-LAL, FB-NO and EB-LAL; unidirectional connections are seen from NO-LAL, PB-NO and EB-NO. The volumes of the adult neuropils were adapted from [22]. The volumes of the larval neuropils were drawn via CATMAID using the .b and .d parts of the neurons contributing to each.



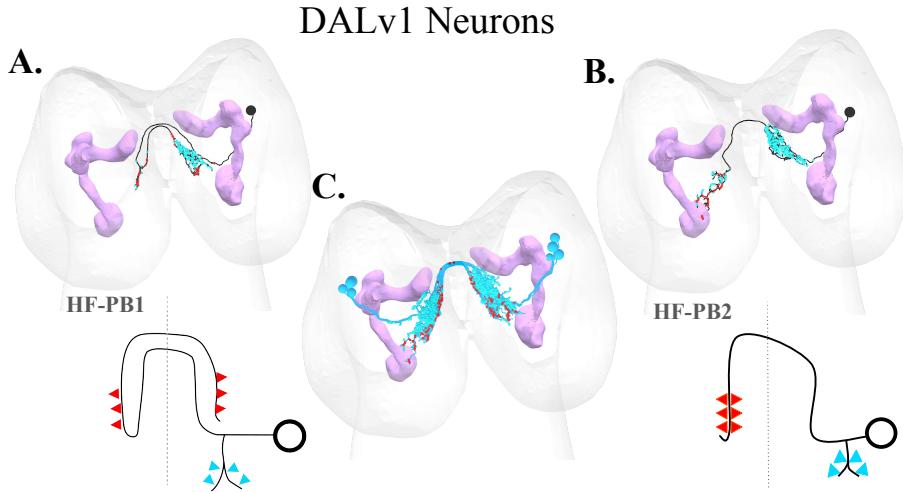
**Fig. 3.3 Larval CX neuron boutons define the volumes of the 4 main CX neuropils.** Posterior and lateral views of neurons that contribute boutons ("b") to each of the 4 neuropils. In concordance with the adult, the PB is the most dorsal and posterior neuropil of the whole brain; the FB occupies an intermediate medial position; the EB is the most medial anterior neuropil (same dorso-ventral level as the mushroom body medial lobe but even more anterior); and the NO are medial and ventral. Note that the white medial space in the larval cartoon is truly devoid of brain tissue: the larval CX neuropils line the medial boundary of the brain hemispheres, with the pharynx occupying most of the intermediate space.

CX Core Neurons	Other Names (CX or MB)
FB.d, NO.b	FB-NO 1, FB.d.1
FB.d, PB.d, NO.b	FB.d.1, CN-34, MB2ON-119
FB.d, PB.d, NO.b	FB.d.1, MB2ON-204
FB.d, NO.b	FB.d.1, MB2ON-201
EB.d, EB.b, LAL.b	MB2IN-124, MB2ON-79
EB.d, LAL.d, EB.b	RN4, FBN-19, MB2IN-37, MB2ON-112
EB.d, LAL.d, EB.b	RN4, FBN-21, MB2IN-42, MB2ON-128
EB.d, EB.b	RN3, MB2IN-122, MB2ON-71
EB.d, EB.b	RN1/2a, FBN-20, MB2IN-38, MB2ON-115
EB.d, EB.b	RN1/2b, FB2IN-10, MB2IN-68, MB2ON-266
FB.d, FB.b	eDAN-2
FB.d, FB.b	MB2ON-125
FB.d, LAL.b	FB.d.2
PB.d, FB.d	FB.d.2
PB.d, NO.b	MB2ON-241

**Table 3.4 CX Core Neurons** The table illustrates, in the first column, the CX Core neurons in nomenclature adapted from Wolff et al., 2015[95], depicting the location of the dendrites (.d) axonal butons (.b) in the Central Complex Neuropils. Each neuron is listed alongside their CX neuropil-specific nomenclature, and/or their MB nomenclature

intersect and synapse onto the dendrites of the PB columnar neurons; however, we found a larval lineage (DALv1) whose axons are bilateral and project to the appropriate area, and is developmentally related to another central complex lineage (DALv23). This suggests that neurons from non-central complex lineages may be recruited temporarily during the larval period, in a pattern reported so far for the mushroom body (see Discussion; [89]).

**Larval PB horizontal fibers:** Among neurons of the DALv1 lineage, 4 left-right pairs (named HF-PB for "Horizontal Fiber PB") project their axons bilaterally and across the dendrites of the columnar neurons. 3 of the 4 pairs present an unusual axon configuration: first, they project contralaterally to drop their first output synapses, with the axon then crossing the midline a second time to return back to the same ipsilaterally corresponding location to again drop presynaptic sites. This peculiar axon configuration is unique among all neurons of the entire brain of the larva ([93]) and suggestive of potentially a delay line for comparing left-right sensory inputs. The 4th pair first drops presynaptic sites ipsilaterally and then its axon crosses the midline until reaching the corresponding contralateral location to synapse again (3.4). These neurons are PB.b neurons since they contribute axonal butons to the PB. Several of these neurons have their dendrites enclosed in the FB (are FB.d neurons), making them Core CX neurons.



**Fig. 3.4 PB Horizontal Fibers (HF-PB).** Two types of horizontal fiber neurons are shown, each with a morphological reconstruction (top) and a simplified schematic (bottom). The mushroom body is shown in magenta. Input synapses (dendrites) are indicated by blue arrows, while output synapses (axons) are indicated by red arrows. Panel **A.** shows HF-PB1 neurons, characterized by a double-crossing axon; panel **B.** displays HF-PB2 neurons, with outputs projecting only contralaterally; and panel **C.** the four bilateral pairs of HF-PB neurons shown together.

The presynaptic outputs of DALv1 neurons are symmetric, in that they contact the same homologous pairs of left-right neurons which are predominantly neurons of the columnar system from the DM1-DM4 lineages.

	PB Horizontal			PB Columnar						
	PB to NO, MB2ON-204 _r	PB to NO, MB2ON-204 _l	PB to NO, MB2ON-241 _r	PB to NO, MB2ON-241 _l	PB to EB, MB2IN-195 _r	PB to EB, MB2IN-195 _l	PB Descending _1_l	PB Descending _1_r	PB Descending _2_l	PB Descending _2_r
HF-PB1_r					1	13	15	22	26	
HF-PB1_l					1	11	9	23	27	
HF-PB3_r	12	21	17		8	10	9	13	13	18
HF-PB3_l	17	22	7		8	11	14	10	13	19

Table 3.5

The axons of these 4 pairs of HF-PB neurons are tiled dorso-ventrally, falling into two bilaterally symmetric groups which we interpret as defining 2 + 2 bilaterally arranged PB compartments, each innervated by 2 pairs of axons (Figure 3.4C).

The dendrites of these 4 pairs of DALv1 neurons (HF-PB) are ipsilateral and dorsal, receiving polysynaptic inputs from vision and olfaction, like in the adult PB ([38]). In the larva, we found that these multi-sensory inputs to the horizontal fibers of the PB are mediated by Convergence Neurons (CN-53 and CN-54, among others; [16]) that, as their name indicates, integrate inputs from both Mushroom Body Output Neurons (MBONs) and from the Lateral Horn (LH) such as olfactory and visual PNs [17]). This circuit architecture indicates that sensory inputs arriving to the larval PB will have been modulated or gated by previously established associative memories, with implications for spatial navigation.

Three more larval lineages contribute HF-PB neurons: the BLAvm (neuron SLR), the BLAd-OL (neuron MB2ON-63), and the DPMm2 (neuron ADC1), with one pair of neurons each.

MB2ON-63 presents a bilateral axon similar to the 4th pair of HF-PB (DALv1), and an ipsilateral dendrite that integrates inputs from multiple convergence neurons (CN-54, CN-9), MBONs (MBON-c1, MBON-d1), and sensory PNs (olfactory mPN B1, visual PVL09).

SLR presents a contralateral axon that spans both the FB and PB, and an ipsilateral dendrite that integrates inputs from MB2ON-63, CN-9, and the FB intrinsic neuron MB2ON-175 (see below), in addition to a long tail of weaker input from ascending neurons relaying information from the somatosensory system.

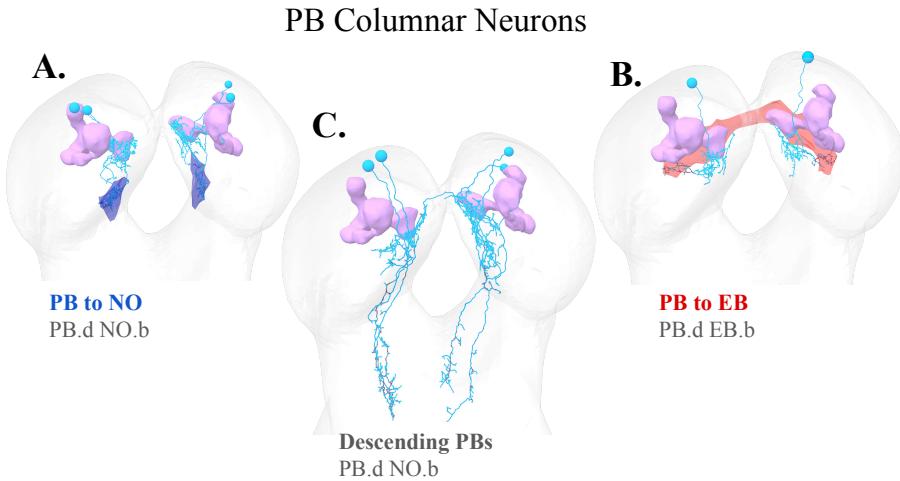
ADC1 presents an ipsilateral dendrite projecting to the posterior brain and a bilateral axon circumscribed to the PB. These neurons integrate inputs from multiple sensory PNs (mPN B2, mPN 5 (also known as mPN BAmd1-g), mPN A1, and weakly from others), a convergent neuron (CN-35), MB2ON-94, and a few others weakly. Their axons target primarily HF-PB neurons (DALv1), but also convergent neurons strongly (CN-56, CN-15, CN-35).

#### ***Larval PB columnar neurons:***

In the larva, the columnar system consists of neurons from 4 central complex lineages (DPMpm1, DPMpm2, DPMm1 and CM4) that also generate the columnar neurons of the adult (DM1, DM2, DM3 and DM4, correspondingly: these are the same lineages with different names for the larva and the adult for historical reasons). Larval columnar neurons present small, narrow dendrites circumscribed within the 2 + 2 compartments defined by the axons of the HF-PB (DALv1) neurons, from whom they receive synapses. These are catalogued as PB.d neurons since they contribute their dendrites to the PB.

Among the columnar neurons, a subset project their axons directly to the NO (Fig. 3.5A), and another subset project directly to the larval EB (Fig. 3.5B).

We did not find among the larval columnar neurons any whose axon would project to more than one CX neuropil, despite such types being common in the adult [94, 95, 38].



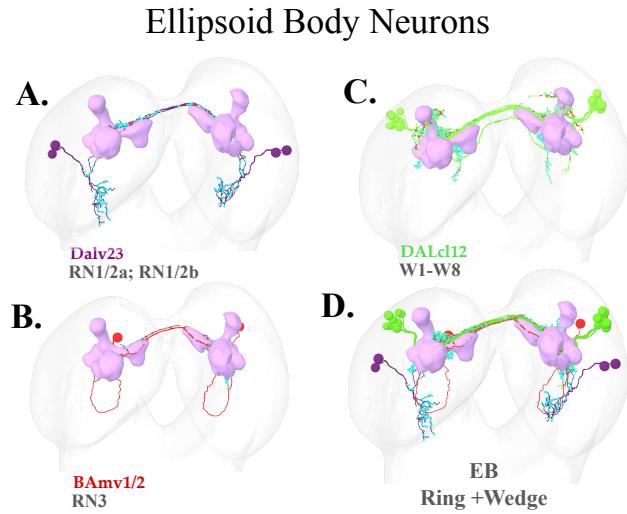
**Fig. 3.5 PB columnar neurons.** The three types of columnar neurons are shown. The mushroom body is shown in magenta. **A.** Neurons projecting from the PB to the NO (PB.d NO.b), with the NO neuropil shown in dark blue. **B.** Neurons projecting from the PB to the EB (PB.d EB.b), with the EB represented by the red structure beneath the mushroom body. **C.** Descending PB neurons projecting toward the SEZ or the VNC.

Beyond the canonical columnar neurons projecting to other CX neuropils, we found some whose axons descend directly to the SEZ or nerve cord (Fig. 3.5C).

### 3.2.2 Ellipsoid Body

**Larval EB Wedge neurons:** In the larval brain, we found a group of 8 pairs of reciprocally synaptically connected neurons from larval lineage DALc12, known to produce Wedge neurons in the adult, so we named them Wedge neurons. Both their dendrites and axons are very small, and tiled medio-laterally, defining 8 compartments with one single neuron pair contributing to each (Fig. 3.6C). We found an additional pair of neurons from larval lineage DALv23 (which produces ring neurons in the adult) with the same connectivity pattern as Wedge neurons (Fig. 3.6B). All wedge neurons have contribute both axons and dendrites to the EB, making them EB.d.b neurons, and Core CX neurons, accordingly.

While Wedge neurons make both axo-dendritic and axo-axonic synapses onto each other (like the AL Picky LNs do; [5]), their dendrites integrate inputs from a variety of sources, including MBONs (MBON-e1, MBON-e2, MBON-g1, MBON-g2, MBON-b3, MBON-m1, and weak inputs from more), convergence neurons (CN-14, CN-25, CN-62, CN-38), and MB feedback neurons (FBN-13, FBN-19, FBN-21), indicating that the EB is intimately and intricately involved with the MB (see below). Wedge neurons, like the adult, receive further



**Fig. 3.6 Ellipsoid Body Neurons** Ring and Wedge Neurons with their corresponding lineages. The mushroom body is shown in magenta as a landmark in the larval brain. **A.** Ring neurons of lineage Dalv23, namely RN1/2a and RN1/2b; **B.** Ring neuron RN3 originating from lineage BAmv1/2; and **C.** The 8 EB wedge neurons (W1-8) originating from DALcl12 lineage. Panel **D.** depicts all these neurons stacked together to form the EB

axo-axonic synapses from Ring neurons (see below; RN1/2, also known as FBN-20; and RN3).

#### *Larval EB Ring neurons:*

We found one pair of neurons (RN3) of the larval BAmv1/2 lineage (corresponding to adult lineage LALv1 known to generate ring neurons) that receive visual input via PB columnar neurons, and reciprocally synapses axo-axonically with larval Wedge-neurons (Fig. 3.6A). Their axons are fully contained within the space defined by the wedge neurons. Similarly, we found two pairs of neurons (RN1/2) from the larval DALv23 lineage (adult EBa1 lineage, also known to generate ring neurons), synaptically connected like RN1/2 (Fig. 3.6B). We classified all of these as larval EB Ring neurons, all of them having both dendrites and axons inside the EB, making them EB.d.b neurons, and as such, Core CX neurons.

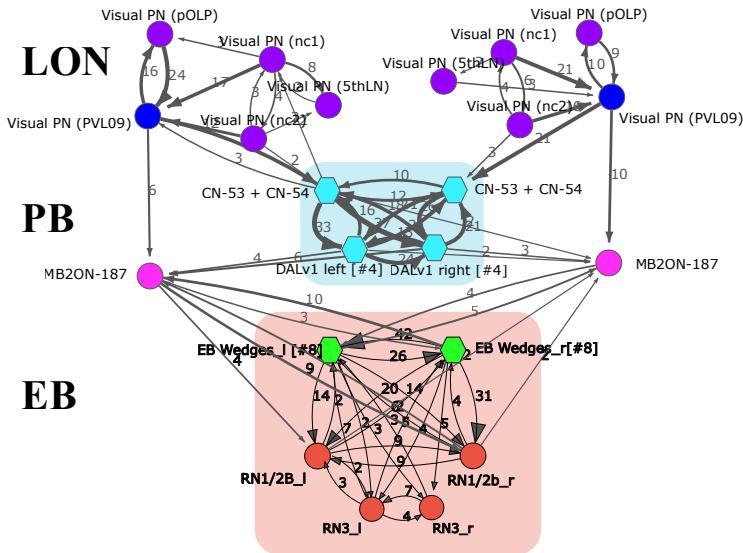
**Additional EB.d Neurons** There are seven more pairs of EB.d (neurons that contribute presynaptic sites to the EB) that didn't fall under ring or wedge neuron categories. Two of these are MB Dopaminergic neurons (DAN-d1 and DAN-g1), another 3 are LAL intrinsic neurons, and the last 2 are MB second order output neurons.

#### *Sensory inputs to the larval EB:*

In the adult, the EB is known to receive visual inputs via a polysynaptic pathway (see Fig. 6 in [38], and Fig. 4 in [64]). In the larva, we find that the main visual PN for negative phototaxis, PVL09 [39], synapses axo-dendritically onto MB2ON-187, which relays sensory

Neuron	RN1/2a_l	RN1/2a_r	RN1/2b_l	RN1/2b_r	RN3_l	RN3_r	RN3_t	RN4_l	RN4_r	RN5_l	RN5_r	RN5_t	RN6_l	RN6_r	RN7_l	RN7_r	RN8_l	RN8_r
RN1/2a_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RN1/2a_r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RN1/2b_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RN1/2b_r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RN3_l	0	0	0	0	2	1	0	0	2	0	0	0	1	0	1	0	1	1
RN3_r	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1
W1_l	0	0	6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
W1_r	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	3	0
W2_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
W2_r	0	0	0	0	0	0	0	0	2	0	1	0	1	0	6	0	0	3
W3_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
W3_r	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
W4_l	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
W4_r	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
W5_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W5_r	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W6_l	0	0	0	0	1	0	0	0	4	0	0	0	0	0	1	0	0	0
W6_r	0	0	0	0	0	0	0	0	5	0	0	0	1	0	0	0	0	0
W7_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
W7_r	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	1	0	1
W8_l	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1
W8_r	0	0	0	0	0	0	0	0	3	0	0	0	0	0	2	0	0	1

**Fig. 3.7 EB Neurons Connectivity.** Both tables display the connectivity patterns among ring and wedge neurons in the ellipsoid body (EB). Each neuron is separated into left (`_l`) and right (`_r`) counterparts to represent lateralization. **Upper table:** axo-dendritic connections (color-coded in the green spectrum). **Lower table:** axo-axonic connections (color-coded in the yellow spectrum).



**Fig. 3.8 Visual Input into the EB.** Input from visual Projection Neurons (Visual PN) to the Ellipsoid Body (EB) via two convergence neurons (CN53, CN54), a pair of PB DALv1s and a second-order Mushroom Body output neuron (MB2ON-187).

inputs from visual and other sensory modalities axo-axonically onto larval Wedge neurons and Ring neurons (Fig. 3.8). MB2ON-187 is named so for being postsynaptic to MBONs (MBON-c1 in particular; [16]). Through MB2ON-187, multiple sensory PNs (PVL09, mgPN 7) and many neurons postsynaptic to MBONs (MB2ONs) synapse onto Wedge neurons (see Suppl. Connectivity Matrix). The latter indicate, again, that MBONs modulate or filter sensory inputs converging onto the EB.

### 3.2.3 Fan-Shaped Body

In the larva, we found a number of putative FB horizontal/tangential cells originating in lineages known to contribute neurons to the adult FB. Characteristically, most present a bilateral axon closely wrapping around the midline, and an ipsilateral dendrite positioned within the superior dorsal protocerebrum (dorsal anterior neuropil) where they integrate numerous inputs from MBON axons. Among the various neurons with dendrites within this very medial neuropil, we find neurons from lineages known to contribute to the adult FB and whose axons project to the putative larval NO, EB, PB and LAL.

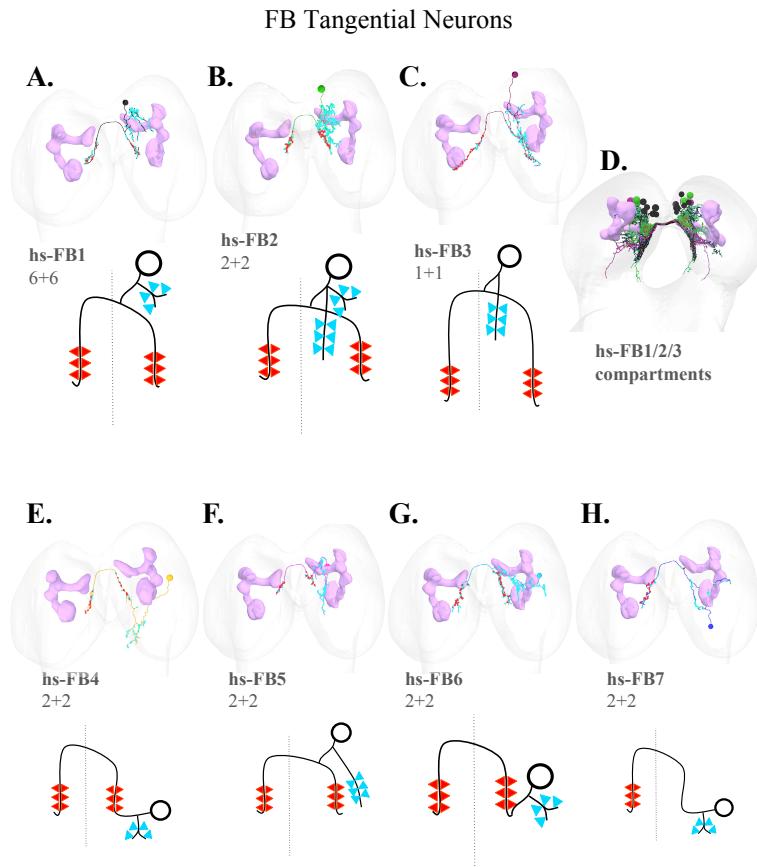
#### Larval FB tangential cells

We found a diverse and large collection of larval FB tangential cell types. All types contribute synapses rather specifically to the FB and are hence labeled as FB.b, a defining feature across them all. The somas originate in a number of larval lineages whose adult

homologs are known to contribute neurons to the adult FB (see above), but also a few from the nerve cord, projecting their ascending axons directly to the FB such as the pCC neurons (a cell type first reported in grasshopper [27] and later in the *Drosophila* embryo [40]). The axons of the pCC project to the ipsilateral FB. The set of ascending neurons isn't complete, for the ventral nerve cord (VNC) remains incompletely mapped.

Among all neurons projecting their axons to the FB, many are brain neurons that do so with a typical bilateral horseshoe ('hs') axon, and hence we named them hs-FB, with a numeric label for each subtype.

The DM1-DM4 lineages that contribute to the adult CX also generate a number of neurons in the larva (larval lineages DPMm1, DPMpm1, DPMpm2, and CM4-vm, respectively). Targeting the FB, there are several major subtypes. First, 6 pairs of neurons (hs-FB.1) with a bilaterally symmetric axon that tightly lines the medial surface in a horseshoe shape, and with a smallish dendrite dorsal and slightly lateral to the FB, within the medial side of the superior protocerebrum. Second, 2 pairs of neurons (hs-FB.2) also with bilaterally symmetric axons but that target the more posterior-lateral FB and beyond into the larval PB, with also ipsilateral dendrites that extend anteriorly and ventrally along the neuraxis. Third, a pair of neurons (hs-FB.3) with bilateral axons placed towards the most posterior end of the FB and perhaps beyond, into the lateral side, and with small ipsilateral dendrites. The axons of all 6 pairs of hs-FB.1 neurons define the ventral layer of the FB, and the axons of the hs-FB.2 the dorsal one, which is shorter and more anterior. The hs-FB.3 axons project in between the other two types but also cover the posterior-dorsal area that hs-FB.2 doesn't (Fig. 3.9). The larval BAla34 lineage generates sensory PNs, of which two pairs (hs-FB.4) present the typical bilateral axon and their dendrites collect inputs from the ventral posterior brain where ascending PNs from the somatosensory system (mostly mechanosensory) project their axons. One of the pairs is also NO.d (collects inputs from NO.b neurons). The larval BAmd2 lineage contributes two pairs of neurons (hs-FB.5) with a bilateral axon and dendrites that cover a region medial but lateral to the FB, and also far more ventral. The larval DAL11 lineage contributes two pairs of neurons (hs-FB.6) with a bilateral axon and dendrites integrating inputs from the intermediate and lateral areas to the FB, primarily from neurons postsynaptic to ascending mechanoreceptive neurons like A00c [62]. A number of neurons presynaptic to hs-FB.6 are also labeled as FFNs and MB2INs, meaning they converge onto MB DANs, MBINs and OANs [17]. The larval CPa lineage contributes a pair of neurons (hs-FB.7) with a bilateral axon and dendrites that cover the most posterior end of the FB, or right outside, plus sparsely a space lateral to the FB, collecting inputs from polysynaptic pathways originating in somatosensory mechanoreceptive neurons.



**Fig. 3.9 FB tangential cells**, also known informally as "horseshoe" neurons for the shape of their bilateral axons. The seven hs-FB subtypes are shown, each with a morphological reconstruction (top) and a simplified schematic (bottom). Input synapses (dendrites) are indicated by blue arrows, and output synapses (axons) by red arrows. The mushroom body is shown in magenta. Neuron counts (left+right) are given below each schematic. **A–C.** Individual examples of hs-FB.1, hs-FB.2, and hs-FB.3. **D.** Overlay of hs-FB.1 through .3, illustrating the FB compartments they define. **E–H.** Individual examples of hs-FB.4 through .7.

Finally, the DPLal1-3 lineage contributes a pair of small neurons (ip-FB.1) with an ipsilateral-only axon targeting the most posterior lateral side of the larval FB, and with dendrites more lateral that integrate inputs from a variety of neurons, some of which are NO.d.

#### ***Larval FB columnar neurons***

By definition, all larval FB columnar neurons present dendrites in the FB (are FB.d), and are postsynaptic to FB.b neurons.

In addition to generating FB tangential neurons, the DM1-DM4 lineages also contribute 5 pairs of FB columnar neurons. These neurons (FB.d.1) are characterized by ipsilateral-only dendrites largely circumscribed to the FB (except for the Bushy neuron from the DPMpm1/DM3 lineage), and projecting their ipsilateral-only clutchy axons solely to the NO (so they are FB.d-NO.b). Therefore, FB.d.1 are specialized in relaying information from the FB to the NO hemilaterally. Among FB.d.1 we find CN-34, MB2ON-201 and MB2ON-204 [16]. Importantly, 4 of the 5 FB.d.1 pairs also send their dendrites to the PB, making them PB.d neurons as well, therefore PB.d-FB.d-NO.b as well as core cx neurons. This is the closest to the adult PFN, however the adult analogue would be PB.d-FBb.b-NO.b.

The DM lineage (larval CM4-vm lineage) further contributes 1 pair of neurons (FB.d.4) with ipsilateral dendrites in the posterior FB and beyond into an area adjacent to the LAL medially, and a contralateral axon that descends into the VNC, dropping presynaptic sites from the SEZ to the most posterior abdominal segments. Within the brain, FB.d.4 synapses onto some NO.d neurons (e.g., MB2ON-200) and also onto CN-28 [16].

The MB neuroblasts contribute 3 pairs of early-born, non-Kenyon cell neurons (the 'ni' for "non-intrinsic"), named FB.d.2, with ipsilateral dendrites in the FB and a contralateral axon targeting exclusively the LAL.

Then there are a collection of single pairs of neurons, each contributed by a different neuroblast, with dendrites in the FB and their axons targeting widely divergent neuropils, across the brain and also into the SEZ and VNC.

The larval BLAv12 lineage contributes 1 pair of neurons (FB.d.3) with ipsilateral dendrites in the FB and also more medially, and ipsilateral axons targeting exclusively the LAL.

The larval DALcm12-v lineage (adult CREa1) contributes 1 pair of neurons (FB.d.5) with ipsilateral dendrites in the FB and in the area adjacent but medial and ventral to the LAL, projecting their axons ipsilaterally from the NO to the medio-ventral brain and dorsal SEZ. The axons synapse onto a large number of NO.d neurons.

The BAMv12-dor larval lineage contributes 1 pair of neurons (FB.d.6) with compact ipsilateral dendrites within the FB, and a compact short ipsilateral axon immediately dorsal

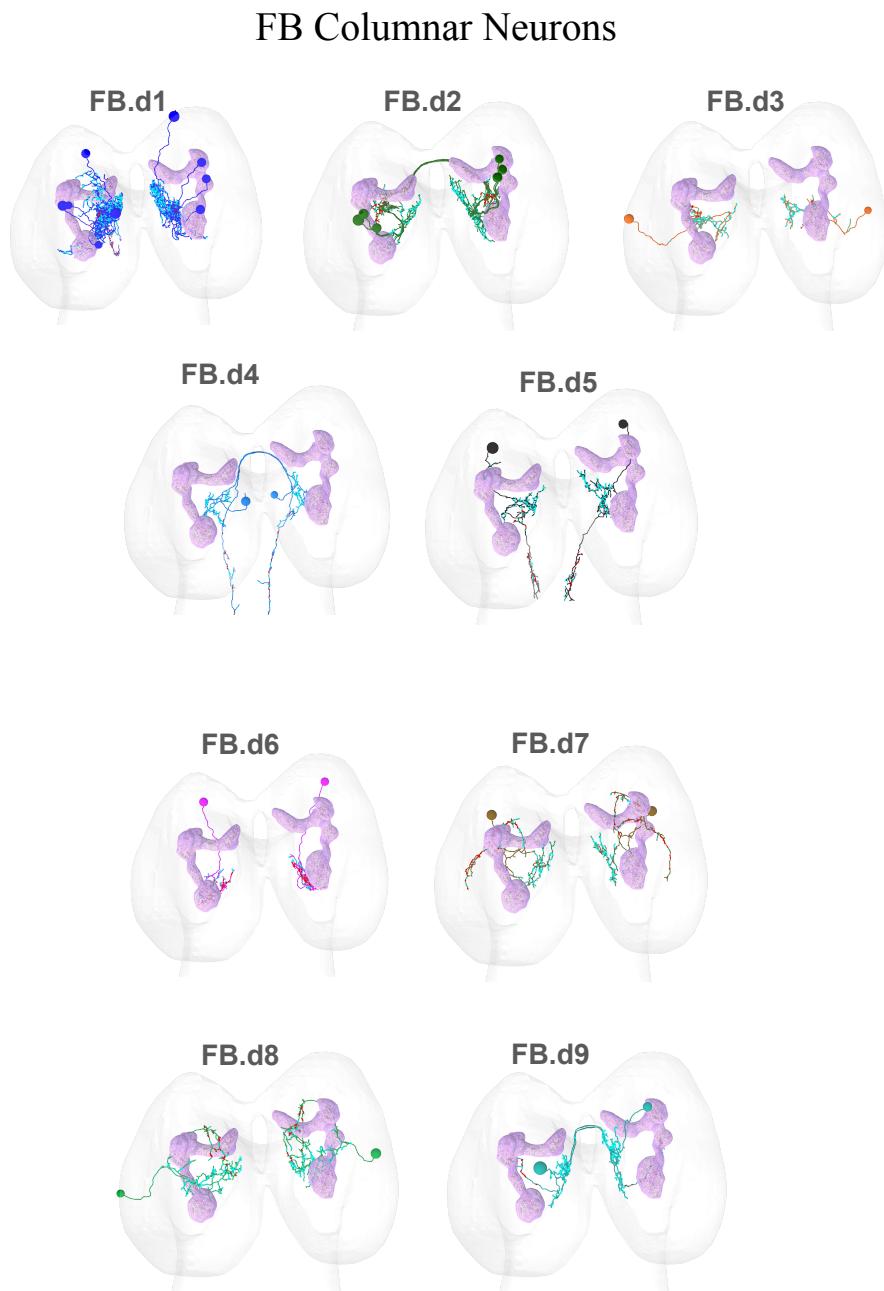


Fig. 3.10 FB Columnar Neurons

on the PB. The FB.d.6 hence serve as a direct relay from the FB to the PB, synapsing onto half a dozen PB.d neuron types.

The BALa12 larval lineage contributes 1 pair of neurons (FB.d.7; also known as FFN-6, [16]) with compact ipsilateral dendrites in the FB, and an ipsilateral axon that targets the superior anterior protocerebrum where it synapses profusely onto the dendrites of DANs and OANs of the MB (DAN-i1, DAN-j1, DAN-c1, OAN-g1). Hence, FB.d.7 serves as a relay between the FB and the MB input neurons, conveying teaching signals for associative memories.

The BLAl larval lineage contributes 1 pair of neurons (FB.d.8) with ipsilateral dendrites within the FB but also extensively lateral to the FB, and with peculiarly curving axons that follow the neuraxis, closely apposed to the dendrites of some hs-FB subtypes (hs-FB.1, hs-FB.2, hs-FB.3) and synapsing onto them.

The DPMI2 larval lineage contributes 1 pair of neurons (FB.d.9, also known as FB-LAL1) with ipsilateral dendrites on the posterior hemilateral FB (with inputs from hs-FB.2, hs-FB.5, hs-FB.6) and also reaching into the PB (with inputs only from ADC1), and a contralateral axon targeting the LAL where they synapse onto LAL LNs, EB.d neurons, and multiple descending neurons (DNs) that project to the SEZ and VNC.

Finally, 3 of the 4 pairs of HF-PB neurons (the ones with a doubly crossing axon) are all FB.d, namely, they have dendrites within the FB and receive numerous synapses from FB.d neurons, in particular subtypes hs-FB.2, hs-FB.5 and hs-FB.6 (with further but weaker inputs from other subtypes). This indicates that the PB horizontal fibers not only integrate inputs from multiple sensory systems and gated by MB outputs, but are also modulated by the FB.

FB Tangential	FB Columnar								
	FB.d.1	FB.d.2	FB.d.3	FB.d.4	FB.d.5	FB.d.6	FB.d.7	FB.d.8	FB.d.9
hs-FB.1	70	10	6	16	25		54	2	
hs-FB.2	145	68	24		43	8	2	19	30
hs-FB.3	35	19				19	18		1
hs-FB.4	3	4					21	1	
hs-FB.5	18	2	1				1	1	
hs-FB.6	166	41	11		6		1	19	18
hs-FB.7	63	16	10			8	50	1	19
hs-FB.8	8	4					5	1	1

Table 3.6 Connectivity between FB Tangential and FB Columnar neurons. Cell shading corresponds to relative connection strength (darker = stronger).

#### Larval FB intrinsic neurons

We found two pairs of neurons (MB2ON-125 and eDAN-2) that are both FB.d and FB.b, corresponding to the third type of adult FB neurons: the intrinsic.

MB2ON-125 integrate inputs across many neuron types, from PB.d columnar neurons to LH output neurons. As the MB2ON-125 name indicates (see [16]), it receives direct synapses from MBONs (just MBON-c1, but a strong connection). Fairly large, its dendrites span approximately the entire spatial domain of the putative larval FB. Postsynaptically we find the CSD neuron [5] and ascending neurons from the ventral nerve cord (VNC), among many others such as FFN-31 (so-called feedforward neurons, from the MB perspective, that bring sensory inputs to MB DANs; [16]).

eDAN-2 is a non-MB dopaminergic neuron (DAN) entirely circumscribed to the posterior-lateral end of the FB. See section on DANs of the CX below for details.

### 3.2.4 Noduli

In the larva we found a set of 21 neurons (10 pairs plus one unpaired) with highly compact, clutchy axons situated in the posterior ventral area of the brain, from lineages DPMm1 (DM1 in the adult), DALcm12, DPMl12, DPLc5, and BAMv12, as well as a few other larval lineages. We define the volume encapsulating all their clutchy axons as the putative Noduli of the larval *Drosophila*, and labeled all these neurons as NO.b.

Among the 21 NO.b neurons in the larva we find FB.d neurons (four pairs of the 5 FB.d.1 subtype including CN-34), convergence neurons (CN-6, CN-16/MBON-p1 [17]), neurons postsynaptic to MBONs (MB2ON-37, MB2ON-241), NO-looper (lineage BAMv12dor), MBON-p1 (a multi-compartment MBON of the MB vertical lobe; [15]), and an unpaired neuron (DLPc lineage). Most NO.b neurons integrate inputs from the MB, as their names indicate (see [16]).

Not a single NO.d neuron projects its axon onto any of the other core larval central complex neuropil, but some project to the LAL (Table ??), supporting a role for the NO as an output neuropil of the central complex.

## 3.3 Mushroom Body and the Central Complex

In the adult **Drosophila**, the Mushroom Body is known to output onto the Central Complex neuropils through the MB Output Neurons (MBONs). At this stage, adult MBONs primarily target the Fan-shaped Body - tangential neurons from the middle layers (4-6) - and the Noduli - via a direct glutamatergic connection from MBON-30 to LCNOp(LAL–NO) neurons which then target the PFN (PB-FB-NO) neurons [38]. Here, we examine the synaptic relationships

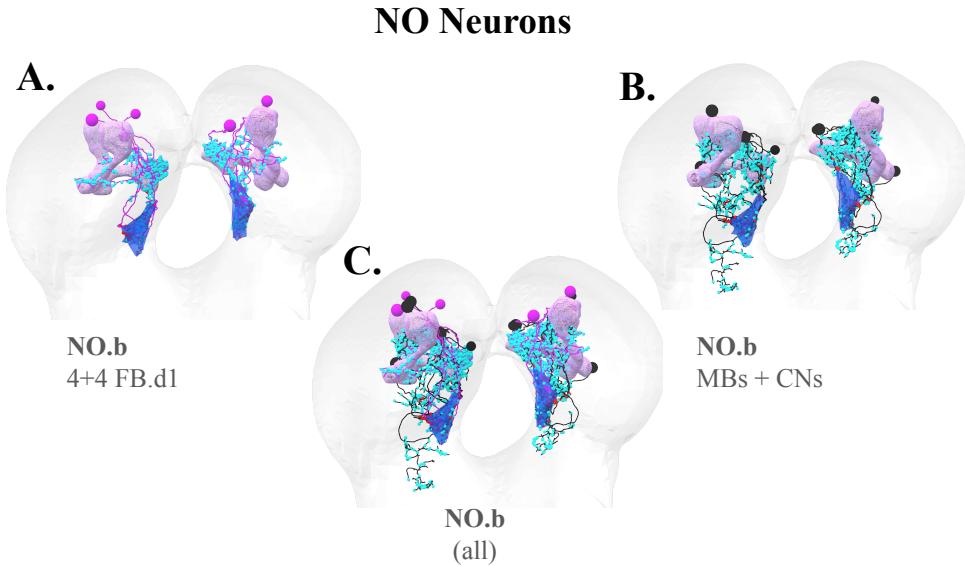


Fig. 3.11 ...

between mushroom body input (DANs, MBINs, OANs) and output (MBONs) neurons and the larval central complex neuropils.

#### A loop between FB and the 'c' compartment of the MB

We found that MBON-c1 synapses onto one FB.b neuron, MB2ON-125. Interestingly, DAN-c1 integrates inputs from an FB.d neuron, FFN-6, which in turn integrates inputs from a few neurons that are directly postsynaptic to MB2ON-125, defining a loop between the MB 'c' compartment and the FB. No other MBON supplies direct or two-hop inputs onto the FB.

#### Reciprocal connectivity between EB ring neurons and the 'g' compartment of the MB

Four MBONs (a2, b3, g1 and g2) are EB.b (i.e., deliver synapses to the EB; Fig. ??). Interestingly, some of these MBONs are monosynaptically interrelated, namely MBON-g1 and -g2 (which promote approach) are GABAergic neurons that synapse onto MBON-a2 (which promote avoidance) [16]. Furthermore, MBON-g1 and -g2 synapse axo-axonically onto an EB ring neuron, RN1/2 (also known as FBN-20; [16]), a core GABAergic neuron of the EB, which in addition to synapsing axo-axonically reciprocally onto EB wedge neurons also synapses onto an EB.d neuron, DAN-g1. Therefore, the output of the MB 'g' compartment (MBON-g1 and -g2) modulate, with GABA, the axon of an EB ring neuron (RN1/2), which in turn synapses onto the dendrites of the teaching neuron of the MB 'g'

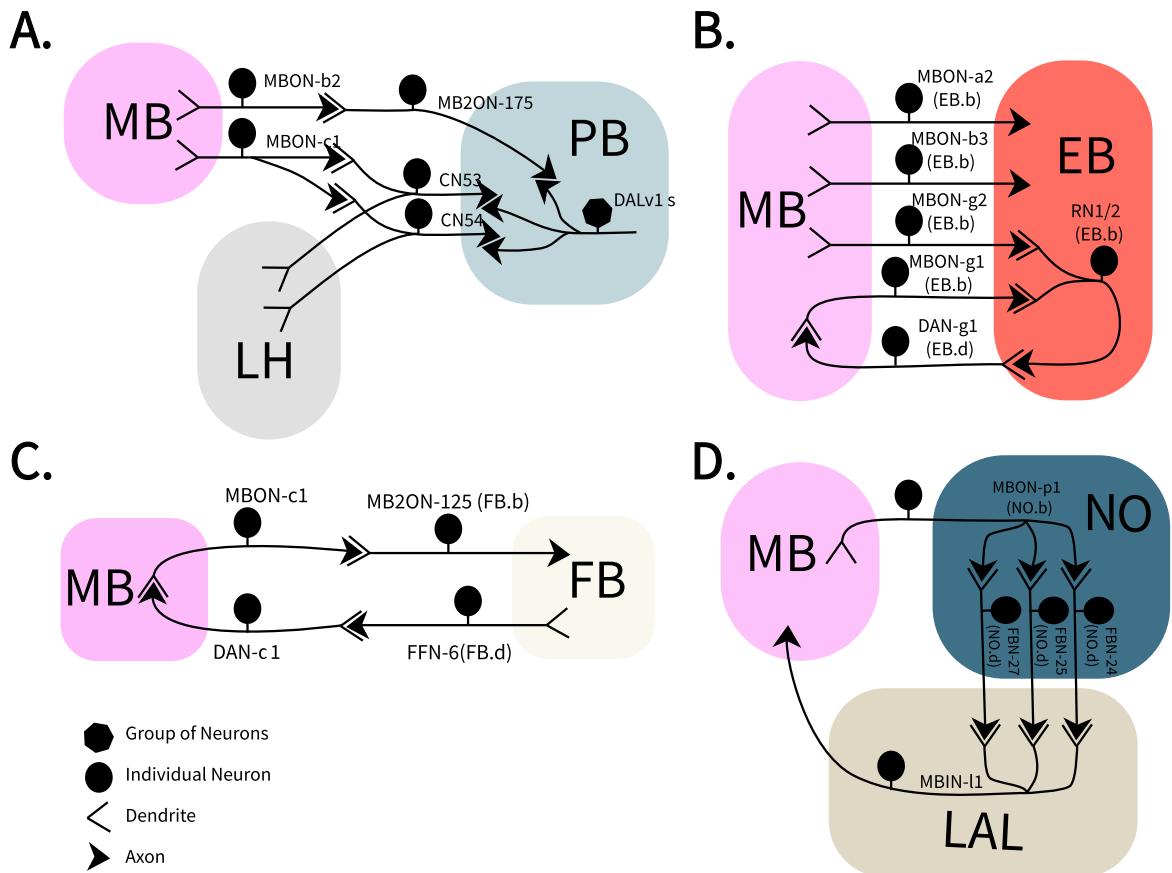


Fig. 3.12 Mushroom Body Connections to the Larval CX

compartment (DAN-g1). This circuit configuration defines a close relationship between an associative learning compartment (MB 'g') and the EB.

Assuming the larval ring neurons RN1/2 are also GABAergic, as they are in the adult [28], the MB 'g' compartment is providing disinhibitory input onto the EB, by means of MBON-g1/g2 inhibiting its ring neurons. This disinhibition could be understood as a learning-based gating mechanism over EB wedge neurons, with features of input space expressed in the Kenyon cell population code, by coincident activity with DAN-g1, modulating the activity of the EB wedge neurons that the ring neurons also synapse onto. Taken together, this implies that, if the larval EB is functionally similar to that of the adult EB, there is a component of learning built-in into the internal representation of the direction of movement.

### A loop between the NO and the MB vertical lobe via the LAL

MBON-p1 is a multi-compartment MBON of the MB vertical lobe that is an NO.b, (i.e., it delivers output synapses to the NO). At the NO, MBON-p1 synapses onto several NO.d neurons, FBN-24, FBN-25, and FBN-27, which are MB feedback neurons [17] that all project to the LAL and synapse strongly onto MBIN-11, a MB input neuron targeting multiple compartments of the vertical lobe. This circuit configuration defines a strong tight loop between the MB vertical lobe and the NO via the LAL.

Note that the dendrites of MBIN-11 are entirely contained within the LAL compartment. In addition, these three feedback neurons also synapse weakly onto DAN-d1.

### The MB modulates inputs to the PB

Multiple sensory modalities converge onto the horizontal fibers of the PB (DALv1 neurons) via MB convergence neurons (CN-53, CN-54) and a neuron postsynaptic to MBONs (MB2ON-175). These CNs were previously described as integrating the output of both the lateral horn (LH), which conveys innate pathways, and the mushroom body (MB), for associative memory [16]. Synapses from CN-53, CN-54 and MB2ON-175 onto PB horizontal fiber neurons (DALv1) follow an intriguing pattern of synapsing onto either the dendrite or the axon, but largely not both, with specific target choices among the 4 DALv1 neurons. In considering that 3 of the 4 DALv1 neurons (PB horizontal fibers) present an unusual bilateral axon that first deploys output synapses contralaterally and then ipsilaterally (Fig. ??A), the observed pattern of selective axo-dendritic and axo-axonic connections has implications for the modulation of the output of the unusual axons of DALv1 neurons.

In summary, from the perspective of the PB, we find the following circuit architecture: the multi-sensory convergence onto the PB horizontal fibers is directly modulated by the MB,

precisely because the neurons that mediate the multi-sensory convergence are themselves CNs (i.e., integrate also MBON synapses in addition to LH inputs): the CN-53 and CN-54. Note CN-54 is in addition a PB.d neuron, integrating inputs from PB horizontal fibers (DALv1 neurons).

Upstream, among various MBONs, MBON-c1 is the most strongly connected to both CN-53 and CN-54, which also integrate inputs from MBON-b1 and MBON-b2. All three are MBONs of the MB peduncle; MBON-c1 has no known function, while MBON-b1 and MBON-b2 promote approach [16].

Of note, the axon of MBON-c1 receives direct presumably inhibitory (GABAergic) inputs from MBON-g1, MBON-g2, and MBON-d1, with all three MBONs participating of circuit loops with other central complex neuropils.

Additionally, neurons directly postsynaptic to MBONs, such as MB2ON-175, in turn directly synapse onto the horizontal fibers of the PB, either axo-axonically or axo-dendritically, in a pattern selective of specific DALv1 neurons.

In summary, not only are navigational decisions such as whether to turn to stimuli or not proceeding not independently per sensory modality but integrated across modalities, as observed before in behavioral experiments [24], but also such integration is modulated by prior memories.

### 3.4 Dopaminergic neurons (DANs) of the larval central complex

Dopaminergic release outside the MB in the adult fly is known to trigger sleep via dorsal FB (dFB) neurons [69], among other potential roles, depending upon the dopamine receptors expressed in the postsynaptic neurons and the circuits the neurons are part of.

The larval MB houses 7 pairs of DANs [15], with several more DANs scattered across the brain [80]. By flip-out of the TH-GAL4 expression pattern that encompasses all DANs [80] followed by immunohistochemistry, we isolated individual neurons from the TH-GAL4 expression pattern and compared their morphology with EM-reconstructed brain neurons [93]. We identified with reasonable certainty the following 5 eDAN types (eDAN for *external* DAN, i.e., not a MB DAN), comprising 6 neuron pairs.

**eDAN-1:** from the larval lineage DPMpm2, this neuron presents an ipsilateral dendrite in the posterior-dorsal brain, and a bilateral axon exactly overlapping with HF-PB dendrites. eDAN-1 integrates inputs from PB.d neurons like CN-54 (which mediates multi-sensory input integration and relays them to HF-PB, modulated by MB output; see above) but also

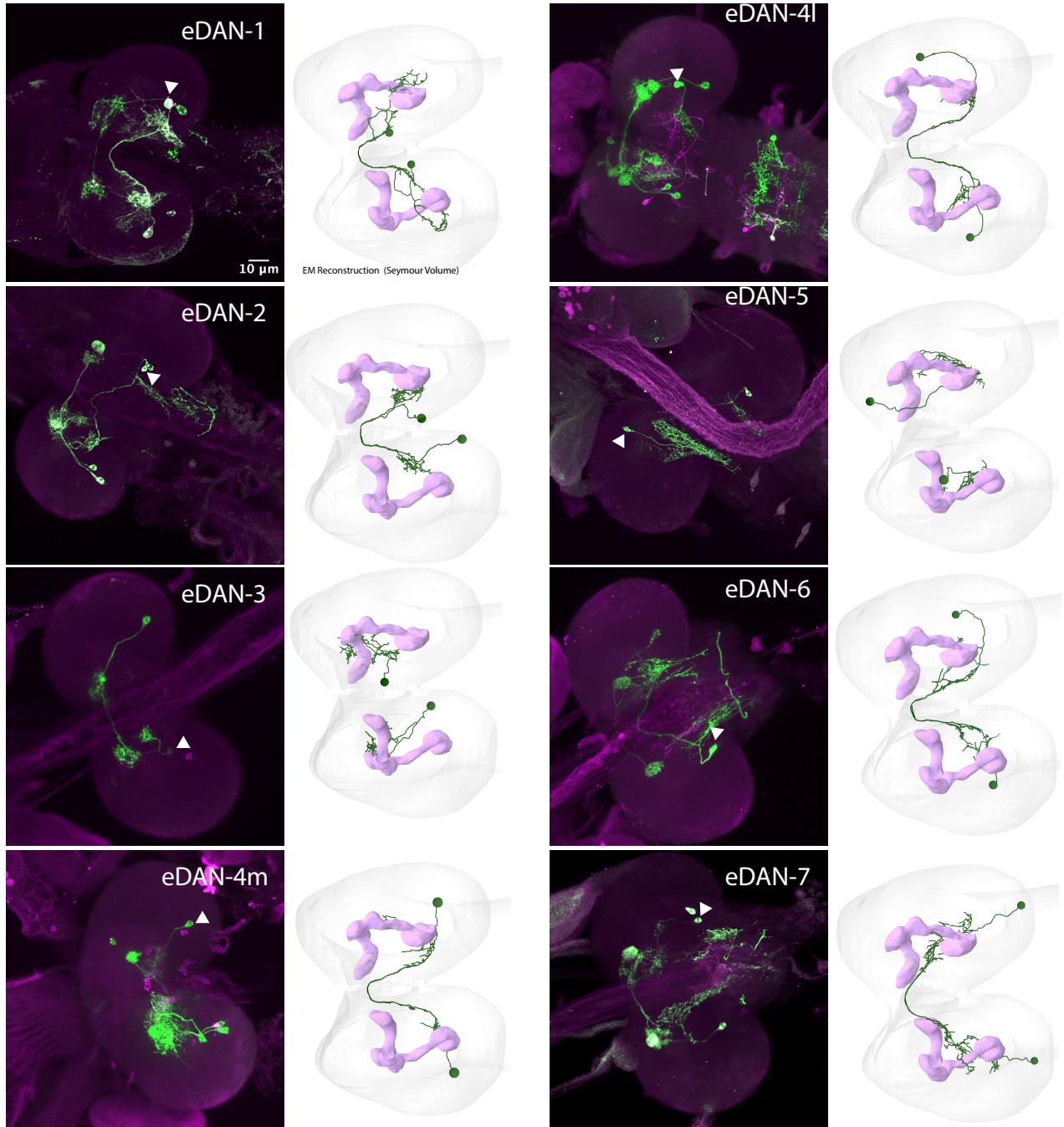


Fig. 3.13 Confocal Images of Immunostained Dopaminergic neurons of the Larval Central Complex

from multiple sensory PNs such as for temperature (Suckerfish PN, Thermo PN 3 and Thermo PN 5), olfaction (mPN A3), and for unknown sensory modalities (Suckerfish PN 2, from unknown sensory MN-Sens-B2-ACp-21 and -22; [59]), and also from PB.b neurons like MB2ON-63. The axon of eDAN-1 synapses onto multiple PB.d neurons (MB2ON-187, CN-15, CN-54, ADC1, FB-LAL1, and SP2-1) and weakly onto HF-PB neurons.

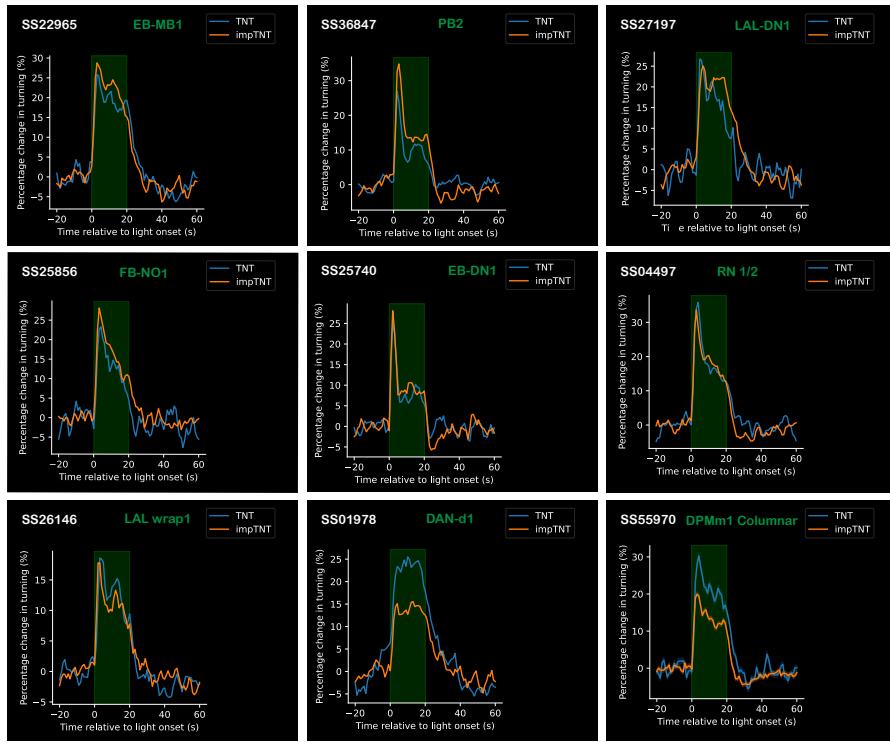
**eDAN-2:** from the larval lineage CM4-dm, this DAN presents a small, compact ipsilateral dendrite and a contralateral axon on the corresponding contralateral hemisphere right at the posterior end of the FB. eDAN-2 integrates inputs from FB neurons (strongly from FB.d.6, hs-FB.3, hs-FB.1, and weakly from many more). Its axon synapses onto MB2IN-195 (which is presynaptic to EB Wedge neurons), multiple FB neurons (hs-FB.3, hs-FB.1, FB.d.7 (FFN-6)), and weakly onto MB2IN-191 (the octopaminergic VUM of the CX).

**eDAN-3:** also known as MB2IN-139 [16], this neuron is from the larval lineage DPMpl12. Its dendrite is ipsilateral, sitting lateral to the FB but also extending into the LAL. The eDAN-3 axon targets a region dorsal to the LAL, housing the dendrites of many EB.d neurons onto which it synapses, such as MB2IN-114, EB-DN1, MB2ON-17, EB wedge neurons (only W1), and many more neurons such as convergence neurons (CN-30, CN-37, CN-38, CN-41, CN-42, CN-43), MB2ON-256, and a peculiar FB.d.1 neuron (Bushy).

**eDAN-4:** this type consists of two nearly identical neurons that share most inputs but differ only slightly in their outputs, since their axons are juxtaposed but tiled medio-laterally. From the larval lineage DPMpl12, they present an ipsilateral dendrite in the posterior ventral brain and a contralateral axon in the posterior intermediate brain, beyond the limits of the FB proper. Both integrate inputs from numerous EB.d neurons like MB2IN-124, but only eDAN-4l (lateral axon) receives synapse from hs-FB.3. The axons of both eDAN-4 synapse onto some NO.d neurons like MB2ON-248 (whose dendrite has a domain in the NO and another outside where it meets the axon of both eDAN-4) and of other unidentified neurons (lasso-top 3, DALcm12-v descending), but only eDAN-4l synapses onto convergence neurons (CN-9, CN-26), and only eDAN-4m synapses onto hs-FB.5 and hs-FB.7.

**eDAN-5:** from the DPMpm1 larval lineage, this neuron's dendrite lays posterior to the LAL and projects its axon inside the lateral LAL. The dendrite integrates inputs from EB.d neurons, MB2IN-195, MB2ON-67, and sVUM2mx. The axon targets weakly but axo-dendritically an EB Ring neuron (RN1/2), and more strongly other neurons (MB2ON-67, MB2ON-78, MB2ON-68).

According to [80] there are further non-MB DANs yet to be identified in the larval brain connectome. Note an effort was made to relate the eDANs we could identify to non-MB DAN names in [80] but the resolution mismatch was too great to bridge, except for eDAN-1 which is most likely named "DM3" in [80].



**Fig. 3.14 Loss-of-function Behavioral analysis of CX neurons expressing TNT and impTNT(disabled TNT)** The name of each split GAL4 line is written in white and their corresponding neuron name in green. Stimulation via green light is highlighted in green from 0-20s. The plots show a time-series of larvae's turning rates, colored in blue for larvae expressing TNT and orange for larvae expressing impTNT

### 3.5 Behavioral Assays - Loss of Function Analysis during light stimulation

We identified genetic driver lines for eight neurons of the larval central complex: EB-MB1, PB2, LAL-DN1, LAL wrap1, FB-NO1, EB-DN1, RN1/2, plus DAN-d1, which is an EB.d (i.e., integrates inputs from the EB). We quantified larval turning behavior following targeted inhibition of each of these driver lines via Tetanus neurotoxin (TNT). Control animals expressed the inactive variant, Impotent Tetanus (ImpTNT). Given that the central complex is classically implicated in visually guided navigation, we used green light stimulation as the sensory stimuli.

We found that expressing TNT did not show significant changes to turning rates for most neurons when compared to controls in response to green light stimulation, with the exception of DAN-d1 3.14.

Neuron Name	Other names	Split Line	.b	.d	Lineage
DAN-d1	FB-33	SS01978		EB.d	CPb
LAL wrap 1	MB20N-116	SS26146		LAL.d	DALcl12-v
FB-NO 1		SS25856	NO.b	FB.d	DPMl12
EB-MB 1	FB2IN-12(Mickey Mouse)	SS22965		EB.d	BLP1/2
RN 1/2	FBN-20, MB2IN-38	SS04497	EB.b		DALv23
EB-DN 1	MB20N-75	SS25740		EB.d, LAL.d	DPMpm1
LAL-DN 1		SS27197		EB.d	DALd
PB2	PB horizontal fibers	SS36847	PB.b		Dalv1

Table 3.7 **Neurons tested for LOF** Neuron names, corresponding split GAL4 line used for LOF experiments, and lineage information.

### 3.6 Neural activity in response to blue light stimulation

We were curious if the identified putative central complex would be responsive to light stimulation. We monitored the activity across the entire larval brain in response to stimulation of Rh5 (blue sensitive) photoreceptors. Photoreceptors (the Bolwig Organ) are located outside of the Central Nervous System(CNS) of Drosophila. We thus expressed EGFP fluorescent tag in these neurons(Rh5s) to be to ensure they are present during dissection of the CNS and that they are preserved for mounting the sample in the glass capillary prior to Calcium Imaging. We created a final line that expresses green fluorescent RGECHO (a calcium indicator of neural activity present cytosol) and red fluorescent IRFP (which brightens the cell nuclei very well and allows visualisation of cell position) and green fluorescent Rh5 photoreceptors.

Upon blue light stimulation, robust calcium transients in multiple regions of the larval brain were observed. Amongst the CX neuropils, we expected the neuropil with the most visual input (Protocerebral Bridge) to be reliably responsive to photoreceptors. To test this, the brain was segmented into distinct anatomical regions using manual annotation. Regions corresponding to the optic lobe (OL) - to confirm functional photoreceptors - the putative Protocerebral Bridge, and the MB - as a control - were delineated (Fig. 3.15). based on anatomical landmarks and lineage tracing data. Fluorescence intensity changes  $\Delta F/F_0$  were quantified for each region before, during and after blue light stimulation.

The Optic Lobe (OL) was reliably activated in response to light in sample 1,3 and 5 samples which confirms intact and functional photoreceptors. For sample 2 the left OL significantly less responsive than the right, indicating possible tissue damage on that side of the brain. Similarly for sample 4 the right side is less responsive than the left. Notably, across all samples, the OL exhibited a markedly larger  $\Delta F/F_0$  response compared to other regions of interest, creating a masking effect in data visualization. Specifically, the large

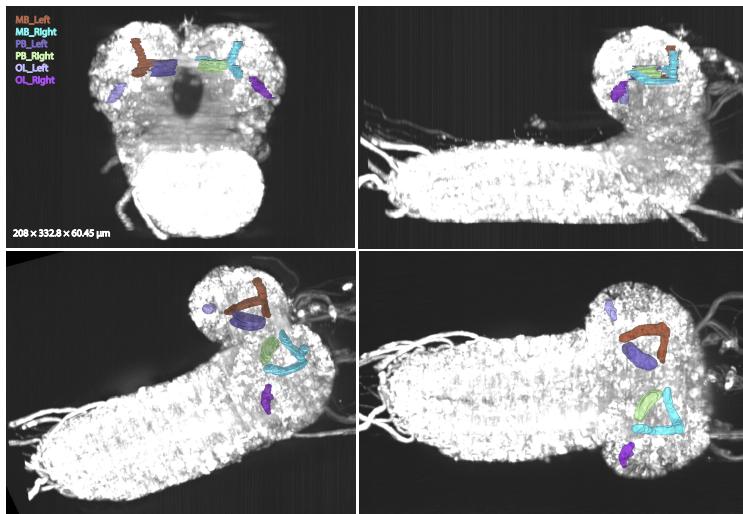


Fig. 3.15 Lightsheet Volume Segmentation

amplitude of OL activity expanded the y-axis range, compressing the apparent variability in other regions and obscuring meaningful differences between the PB and the MB. To better resolve the relative dynamics among the remaining regions, the OL traces were excluded from subsequent analysis and the data was replotted and presented side by side with the original in figure 3.16.

When compared to the control (MB), the larval Protocerebral Bridge (PB) exhibited higher amplitude calcium transients in samples 2, 4, and 5, whereas both neuropils showed similar activity in samples 1 and 3. Interestingly, the two samples with one inactive optic lobe (samples 2 and 4) displayed a more pronounced difference between PB and MB activity, suggesting that unilateral OL impairment may enhance the relative responsiveness of the PB to visual stimulation. This observation may indicate compensatory mechanisms or altered circuit dynamics in the presence of partial sensory deprivation. Overall, there seems to be a higher sensitivity to blue light from in PB compared to the MB, supporting the hypothesis of a functional role in visual input processing (Fig. 3.16). However, the effects aren't as significant as expected, possibly due to small sample size, suggesting the experiment could be underpowered.

### 3.7 Descending Neurons from CX

129 neurons descending to VNC 93 neurons descending to SEZ 216 total descending layer 1 annotated as: 'cx descending l1' (56 neurons) 25.6% 569 second order descending layer 2 annotated as: 'cx descending l2' (71 neurons of 569) 12.4%

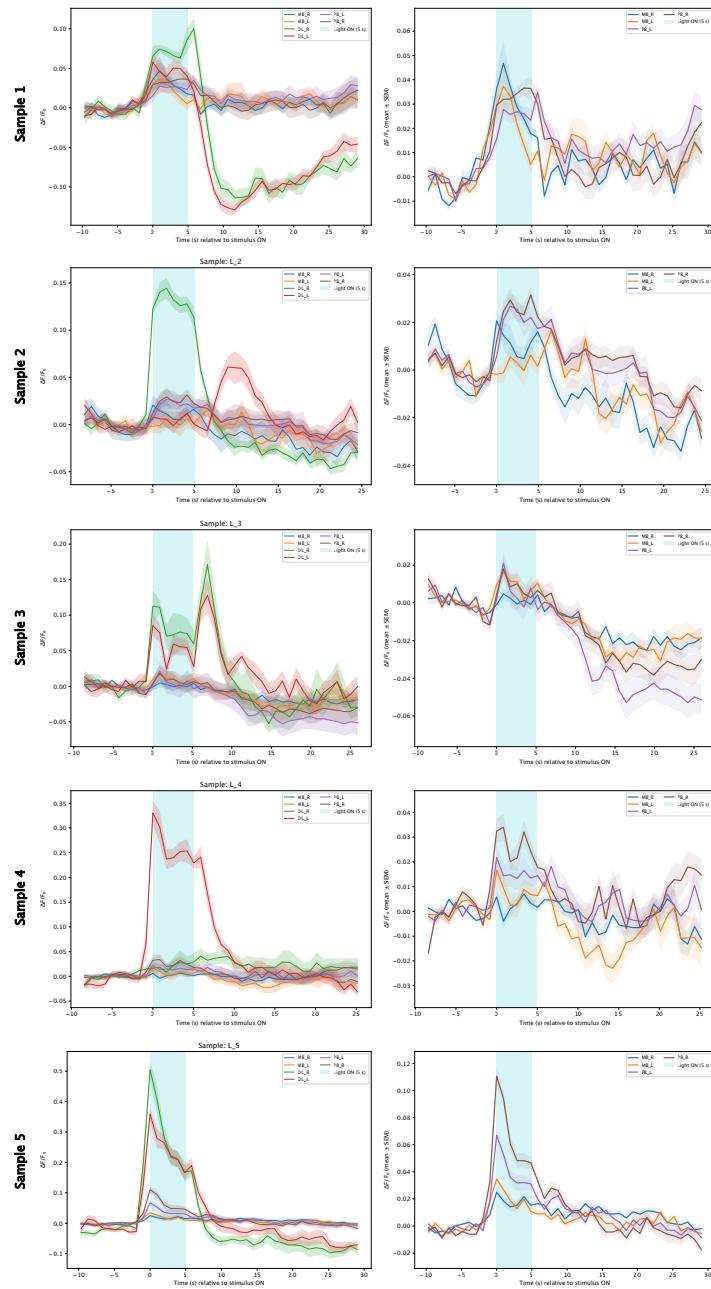


Fig. 3.16 Neural Activity of the Larval Brain in response to Photoreceptors Rh5 Stimulation



# **Chapter 4**

## **Discussion**

Is there a Navigational Centre (Central Complex) in the Larval Drosophila?

The similarities between the larval Central Complex and the adult Central Complex  
PB,EB,FB,NO

Relation to accessory structures such as the LAL Sensory Biases: olfaction vs photoreception  
Central Complex relation to the Mushroom Body (Learning and Memory Centre of the fly)  
iii. Functions of the Larval central complex 1. Network connectivity predictions 2. Does biological data confirm our intuition? 3. Conclusions about the neural functionality iv. What we now know v. Expectations for the future vi. Can this teach us universal components of multisensory integration

### **4.1 Multisensory integration**

Gepner et al., 2015 demonstrated that Larvae have to integrate visual and olfactory gradients, with convergence of these sensory systems before decision to act on them. Exposed larvae to visual and olfactory input - blue light and optogenetic activation of appetitive ORNs No competition between types of taxis. multisensory integration happens immediately before the decision to navigate. Only one coherent representation Why is it that the information isn't processed at the time of decision making - i guess because command like neurons

### **4.2**

Our inquire into the nature of a fraction of neurons in the remaining *terra incognita* of the larval brain of the fruit fly yielded a series of neurons, neuropils and circuits with undeniable developmental, connectivity, and anatomical similarities to the set of core neuropils of

the central complex of the adult fly brain. The key anatomical difference of split brain hemispheres and the very early arrest of neuroblast proliferation in the larvae of Diptera impose strong constraints as to the extent of the anatomical and cellular similarities between the larval and the adult brain.

Notwithstanding, most larval brain neurons survive metamorphosis, help articulate homologous brain neuropils in the adult [72], and participate of neural circuits in the adult brain. For example, the command neurons for backward locomotion [9], and MB MBINs and MBONs [89].

Intriguingly, while we find that larval brain neuronal lineages contribute the same neuronal cell types to the same CX neuropils as their corresponding adult brain instances do, we also find a number of neurons contributing to the larval CX that originate in non-CX lineages. This pattern has been reported before for the MB [89], with some larval MB neurons later on either undergoing apoptosis or, astonishingly, contributing to CX neuropils after metamorphosis. With the MB being an undeniably homologous structure to that of the adult and the larval Kenyon cells making up the bulk of the adult fly brain's gamma Kenyon cells, the recruitment of non-CX lineages into contributing CX neurons in the larva is perhaps part of a common theme in an animal with a limited neuron budget. The broader context being that the larva of the holometabola is derived [88, 87], an evolutionary novelty that enabled this group of animals to exploit novel ecological niches that, to boot, avoids competition with the adults. In such predicament, it is perhaps not surprising that other larval neuropils similarly to the MB temporarily adopt neurons as their own that will eventually either perish by apoptosis or return to an ancestral cell fate away from the CX.

#### 4.2.1 Navigation, place learning, and memory

The central complex has been associated with place learning (for review see [68]), with the EB in particular being necessary for visual place learning in flies [61]. With fly larvae being capable of local search behavior [47], the structure of the larval central complex and its close interactions with the center for associative memory, the mushroom body, must be examined.

We reported that the 'c' compartment of the larval MB is intimately associated with the FB. Intriguingly, MBON-c1 lacks a known role in associative memory to date, with all tests having been performed for olfactory associative memory [17]. Likewise, we discovered a tight loop between the NO and the MB vertical lobe, by means of neurons that also lack a known function in learning: the multi-compartment MBON-p1, whose dendrites span across the MB vertical lobe, and MBIN-l1, a MB input neuron of unknown neurotransmitter signature and function. Both of these MB compartments ought to be examined experimentally for potential roles in navigation or place learning.

With the NO having a role in the adult fly brain controlling the time course of walking activity [84] and in handedness in locomotion [8], and the larval MB vertical lobe mediating aversive memories [17], our report of a tight loop between the output of the MB vertical lobe and modulatory input onto it via the NO may provide the necessary corollary discharge to adjust MB operations to imminent locomotor activity, potentially laterally biased since both MBON-p1 and MBIN-l1 are both entirely ipsilateral-only neurons.

Furthermore, we found that the 'g' compartment of the MB, whose MBON-g1 and MBON-g2 promote avoidance [16] and its DAN-g1 is implicated in aversive learning [17], is intimately and recurrently associated with the Wedge and Ring neurons of the EB. Two further MBONs, MBON-a2 and MBON-b3, likewise synapse onto EB neurons. Among these, the function of MBON-b3 remains unknown. Intriguingly, both MBON-a2 and MBON-b3 are rare among the MBONs in having an ipsilateral-only dendrite but a bilateral axon, when the arborization pattern of MBONs is most often the opposite: bilateral dendrites and an ipsilateral axon. The ability of these MBONs to differentially discern sensory inputs between the left and right sides of the body is suggestive of a role in lateralized behavioral responses, such as in taxis.

In loss-of-function experiments, the suppression of DAN-d1 with TNT removes excitatory drive from MBON-d1, which is GABAergic [16]. From the connectome we interpret that a neuron postsynaptic to MBON-d1, MB2ON-63, which is a PB horizontal fiber distinct from DALv1, will then receive less GABAergic input. And therefore, MB2ON-63 receives unopposed excitatory input from visual PNs (PVL09) and other excitatory visual neurons (ChalOLP), and from MBON-c1, all of which are cholinergic [50, 16]. We speculate that, if in wild-type conditions the inhibition from the MB via MBON-d1 was potentially subtracting an expected intensity of light, to perform a temporal comparison, without it the animal would no longer be able to assert where the light has increased or decreased, leading to the need for continuing to sample by head casting or turning.

#### 4.2.2 DANs in the FB and PB

In the adult CX, dFB is a DAN that releases dopamine at the dorsal FB and is capable of triggering sleep [69]. Intriguingly, we found a DAN (eDAN-2) among the FB intrinsic neurons, and two additional DANs (eDAN-4l and eDAN-4m) that synapse onto a number of FB.d, FB.b and NO.d neurons. Identifying genetic driver lines for these neurons will enable testing experimentally their potential role in sleep regulation in larvae.

The role of eDAN-1, projecting to the larval PB, could be related to overall responsiveness and alertness of the animal, since there is a report that DANs projecting to the adult PB

mediate increases in aggressiveness [2], and other DANs also projecting to the adult PB decrease sleep [86].

What any of the identified non-MB DANs do awaits the identification of specific genetic driver lines and appropriate experimental setups to study their function.

#### 4.2.3 Conclusion

In conclusion, our interpretation of some of the until now underexamined larval brain circuits as a numerically reduced version of the adult fly central complex is coherent with the evolution of the larval stage in the Holometabola and with the known cell types and overall synaptic connectivity of the corresponding neuropils in adult fly brain, bringing a whole field of study into a life stage of reduced dimensions and numbers of neurons and synapses. Now, with our identification of tight circuit loops between understudied MB compartments and the larval CX, an opportunity opens to examine the neural circuit basis of spatial navigation and place learning in this experimentally tractable animal.

# **Appendix A**

## **Appendix title example**

**example**

**example**



## **Appendix B**

**example2**



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