Reverse Engineering of the Insect Heading Encoding Circuit

Ioannis Pisokas **Barbara Webb**
School of Informatics, University of Edinburgh

Abstract

Understanding neural circuits which have evolved over millions of years to control adaptive behaviour may provide alternative solutions for robotics. Recently developed genetic tools and methods allow us to study the connectivity and function of the insect nervous system at the single neuron level, but can we unravel this complex spaghetti to understand the principles of computation it embodies? We here illustrate the plausibility of such an approach by reverse engineering part of the Central Complex circuit in the insect brain, which is known to be involved in navigational behaviours such as maintaining a specific compass heading and path integration. We demonstrate that analysis of the effective structure results in an orderly circuit forming a ring attractor with an eightfold symmetry, capable of tracking the current heading of the animal.

1 Introduction

Neurorobotics attempts to derive inspiration from neuroscience on how the brain solves problems in order to develop more robust and adaptive artificial agents. The combination of neuroscience with embodied robot agents also provides a platform for testing hypotheses and deciphering the principles on which the brain operates.

A limiting factor in the study of any system, including the brain, is the level of detail at which it can be scrutinised. On the other hand, where detail is available, understanding function may be difficult because naturally evolved neural systems do not obey an overarching structural simplicity principle. Insects have relatively small and simple brains compared with vertebrates and yet solve many similar problems, such as perception, navigation, foraging, homing, reproduction. Recent developments of genetic tools and methods provide us with the unique opportunity to study insect brains at the single neuron level. The relative simplicity together with the fine level of detail available for insect brains affords us with the potential to reverse engineer their neural circuits, understand their operation and derive principles that can guide our design of solutions to problems in robotics.

Recent research in insect neuroscience has focused on the Central Complex, a brain structure that has been preserved through millions of years of evolution and exists across all insect species (Homberg et al., 2011). This brain structure has been implicated in locomotor control (Strauss, 2002; Ritzmann et al., 2012), spatial orientation (Neuser et al., 2008; Triphan et al., 2010; Homberg et al., 2011), visual memory (Liu et al., 2006; Neuser et al., 2008; Ofstad et al., 2011) and path integration (Stone et al., 2017; Cope et al., 2017). The Central Complex consists of five neural formations: the Protocerebral Bridge, the Ellipsoid Body, the Fan Shaped Body, the Noduli, and the Asymmetric Bodies (Wolff and Rubin, 2018).

The neural connectivity of the Central Complex has an intricate and yet topographically regular structure. Tracing the neurons of the whole Central Complex is still an ongoing task, thus reverse engineering the whole structure is currently infeasible. However, most of the neurons innervating two of its structures, the Protocerebral Bridge (PB) and the Ellipsoid Body (EB) have been traced in adequate detail in the fruit fly *Drosophila melanogaster*, by multiple labs, allowing us to attempt to reverse engineer the underlying circuit. Moreover, calcium imaging of E-PG neurons which innervate the PB and the EB, while the fruit fly is walking or flying in a virtual reality environment, has revealed a striking relation of the neural activity to behaviour. Specifically, it has been observed that this neural ensemble maintains a localised spiking activity — commonly called an activity 'bump' — that moves from one group of neurons to the next as the

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animal rotates with respect to its surroundings (Seelig and Jayaraman, 2015; Kim et al., 2017; Giraldo et al., 2018). The activity 'bump' is maintained even when the visual stimulus is removed, and it moves relative to the no longer visible cue as the animal walks in darkness (Seelig and Jayaraman, 2015). Thus, this neural activity appears to constitute an internal encoding of heading, which is strongly reminiscent of the hypothetical ring attractor (Amari, 1977) proposed by Skaggs et al. (1995) to account for rat 'head direction' cells (Taube et al., 1990).

These ring attractor models (Skaggs et al., 1995; Zhang, 1996; Taube et al., 1990; Turner-Evans et al., 2017; Cope et al., 2017) typically consist of a ring of neurons with excitatory connections exciting most strongly their nearest neighbours and with decreasing strength as distance increases. A global inhibition signal, calculated as the sum of the activity around the ring, is applied to the excitatory neurons. The result is that the most active neurons suppress the activity of further away neurons and a unique 'bump' of activity is formed. External stimulation of another neuron in the ring causes the activity 'bump' to move to the new most active neuron and the new attractor state to be maintained. This type of ring attractor model can thus reproduce the phenomena recorded via calcium imaging in the fruit fly as described above. However, it remains unclear whether the actual neural circuit in the animal brain has the same form as this hypothetical ring attractor, or if the phenomena may be produced by a different circuitry.

In recent years, specific neurons with potential roles in this circuit have been identified and traced in increasing detail, as will be described in the next section (Wolff and Rubin, 2018; Wolff et al., 2015; Kakaria and de Bivort, 2017; Su et al., 2017; Green et al., 2017; Kim et al., 2017). In this paper we show that the connectivity of these neurons indeed forms a ring attractor, with an eight-fold symmetry. However there are also some notable differences from the classic ring attractor model, which may contribute to the stability and flexibility of the function.

2 What is the effective circuit?

We focus on a subset of neuron types in the Central Complex that appear to be the key elements of the potential ring attractor circuit. The connectivity of the circuit has been inferred from anatomical data mostly derived using light microscopy, with overlapping neural terminals assumed to have synapses between them (Wolff and Rubin, 2018; Wolff et al., 2015; Heinze and Homberg, 2007, 2008; Pfeiffer and Homberg, 2013). Our model includes the E-PG, P-EG, P-EN and Δ7 neurons. These neurons innervate two of the Central Complex structures, the PB and the EB. The Protocerebral Bridge (PB) consists of nine 'glomeruli' in each hemisphere, arranged one next to the other (Fig 1). The Ellipsoid Body (EB) consists of eight sectors called 'tiles'. Each tile is further divided in two 'wedges' (Fig 2). In our model, the E-PG, P-EG and P-EN neurons are assumed to produce excitatory effect to their postsynaptic neurons while Δ7 neurons are assumed to provide the inhibition, as Kakaria and de Bivort (2017) proposed.

2.1 Inhibitory circuit

First, we focus on the inhibitory portion of the circuit which is composed of eight Δ7 neurons in the PB. Each Δ7 neuron has output synaptic terminals in two or three glomeruli along the PB (Wolff and Rubin, 2018). Each of the output terminals of the same neuron are separated by seven glomeruli, Fig 1a. Each Δ7 neuron has input terminals across all remaining glomeruli of the PB. Thus, all Δ7 neurons have the same pattern of synaptic terminals, with each shifted by one glomerulus, as shown schematically in Figs 1a.

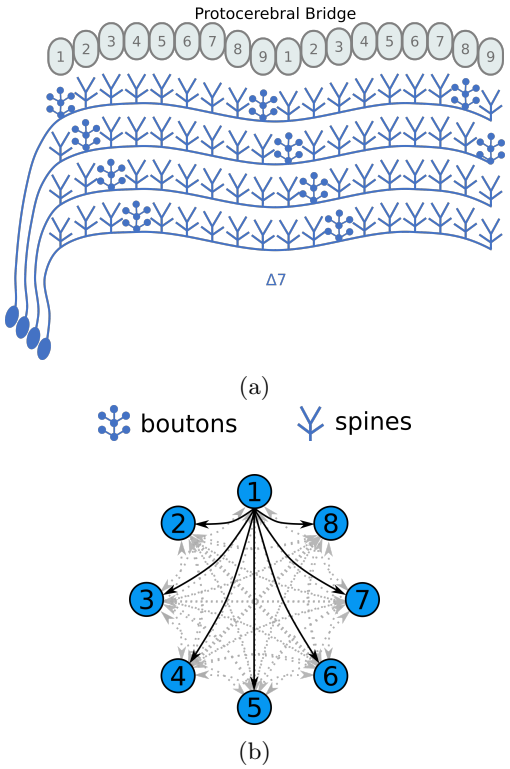

Figure 1: Effective connectivity of the inhibitory (Δ7) neurons. In (a) four examples of how the eight Δ7 neurons innervate the PB are illustrated. In (b) an alternative depiction of the circuit shows how each Δ7 neuron inhibits all other Δ7 neurons.

Within each glomerulus, overlapping input and output synaptic terminals are assumed to form synapses. This results in each Δ7 neuron forming synapses with all other Δ7 neurons in two or three glomeruli along the PB. We reduce these two or three synaptic domains to one single synapse between each pair of Δ7 neurons in order to draw a simplified equivalent circuit in Fig 1b. In this drawing, each blue circle represents one of the Δ7 neurons and arrows represent inhibitory synapses between pairs of neurons. This depiction makes evident that each Δ7 neuron forms synapses and inhibits all other Δ7 neurons. This reveals a global, uniform, inhibition pattern that supports the report of (Kim et al., 2017) that the calcium dynamics observed in *Drosophila melanogaster* can be best modelled by a ring attractor with global inhibition.

2.2 Excitatory circuit

Now, we focus on the excitatory portion of the ring attractor circuit. The synaptic terminals of each of the E-PG, P-EN and P-EG neurons are confined to one glomerulus of the PB, Fig 2. In the EB the synaptic terminals of E-PG neurons are constrained in single wedges (half tiles) while the synaptic terminals of P-EN and P-EG neurons extend to whole tiles. In Fig 2, we have numbered the glomeruli on each PB hemisphere left-to-right, 1-9 and the EB tiles 1-8. We have also numbered neurons by the glomerulus they innervate. For brevity, we denote tile number 1 as W1 and glomerulus number 1 as G1. Neurons are numbered using a numerical subscript, e.g. P-EN$_1$.

Simulating the circuit using the connectivity matrix derived from the neural anatomy of *Drosophila melanogaster* confirmed that, in accordance to calcium and electrophysiology recordings (Turner-Evans et al., 2017), there are two activity 'bumps' along the PB. These activity 'bumps' are centred around neurons innervating identically numbered PB glomeruli. We used this observation to simplify the circuit and derive the effective circuit connectivity.

Under our numbering scheme, each E-PG neuron has synaptic terminals in identically numbered EB tiles and PB glomeruli, Fig 2a. E.g. E-PG$_5$ has synaptic terminals in tile W5 and glomeruli G5 in both hemispheres of the PB. P-EN neurons, however, connect each glomerulus to two tiles, one shifted to the left and one to the right, e.g., they would connect glomeruli G5 to tiles W4 and W6 (Fig 2b). We see in Fig 2c that these P-EN$_5$ neurons form synapses with E-PG$_4$ neurons in W4 and E-PG$_6$ neurons in W6, which innervate glomeruli G4 and G6, respectively. These neurons in turn form synapses with P-EN neurons in these glomeruli, making connections back to W5 and onward to W7 as shown in Fig 2d. This connectivity pattern

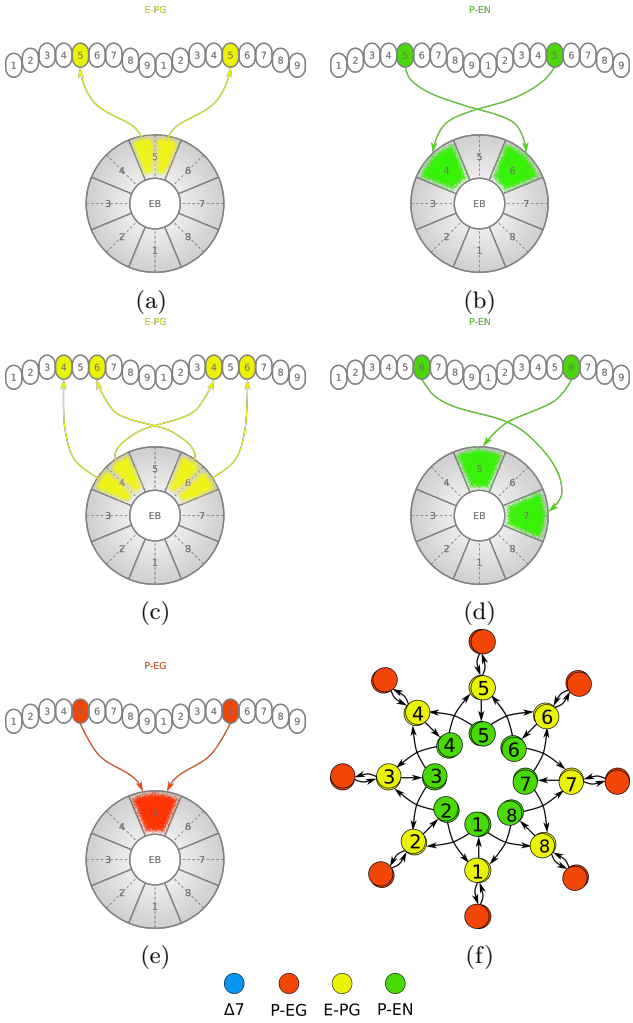

Figure 2: The excitatory portion of the *Drosophila melanogaster* circuit. (a)–(e) examples of E-PG, P-EN and P-EG neurons and their synaptic domains and connectivity patterns (see text for detailed description). (f) Conceptual depiction of the effective connectivity of the ring attractor circuit. Each coloured circle represents one or more neurons with arrows representing excitatory synaptic connections.

continues all the way around the PB glomeruli and EB tiles. Finally, another type of neurons, the P-EG neurons, are innervating equally numbered glomeruli and tiles. They follow the same pattern as the E-PG neurons but with their input and output terminals on opposite ends, Fig 2e.

In Fig 2f we have redrawn this connectivity in a typical network format with neurons represented as circles. This representation removes the details about the anatomical organisation of the EB and the PB while preserving the effective connectivity of the circuit. Since, pairs of E-PG$_n$ neurons connect EB tiles

Wn to PB glomeruli Gn and since the activity is symmetrical in both hemispheres we simplify the circuit by replacing each pair of neurons by one single connection from tile Wn to glomerulus Gn as in Fig 2f. Similarly, due to the symmetrical activation of P-EG$_n$ neurons innervating equally numbered glomeruli those pairs of P-EG$_n$ neurons are also reduced to one unit in the effective circuit in Fig 2f. Finally, each pair of P-EN$_n$ neurons is shown overlapped as they receive the same input but then project respectively to the left or right. It becomes apparent from Fig 2f that the effective circuit of *Drosophila melanogaster* has an eight-fold radial symmetry.

Figs 3a shows the effective interaction of the excitatory and inhibitory portions of each circuit. The E-PG neurons are functionally connected and provide input to the Δ7 neurons. Each Δ7 neuron makes inhibitory synapses to P-EN and P-EG neurons in the same octant, as well to all other Δ7 neurons as previously described. The inhibitory neurons provide uniform inhibition to all eight octants of the circuit.

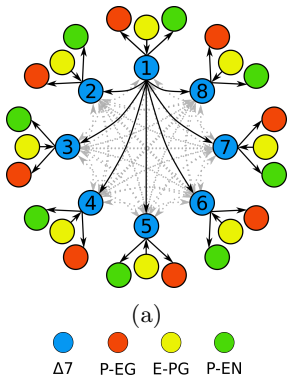

Figure 3: Connectivity of combined the excitatory and inhibitory portions of the ring attractor. Each coloured circle represents one or more neurons with the arrows representing synaptic connections.

3 Model

We implemented a spiking neural model of the circuit using Leaky Integrate and Fire neuron models (Stein, 1967). The heading stimulus is provided as incoming spiking activity directly to the E-PG neurons, corresponding to input from Ring neurons (Young and Armstrong, 2010). This input maps the position of a visual cue, or retinotopic landmark position (Seelig and Jayaraman, 2015), around the animal to higher firing rates of E-PG neurons in the corresponding tile of the EB. The synaptic strengths were modeled as the number of I_{PSC} current units flowing to the postsynaptic neuron per action potential. To determine the synaptic strengths we used an optimisation algorithm to search for values that result to working ring attractors. The values of membrane resistance, capacitance, resting potential, undershoot potential and postsynaptic current magnitude (I_{PSC}) and delay were set to the same values as used by Kakaria and de Bivort (2017). These values are consistent with evidence from measurements in *Drosophila melanogaster*.

Simulating the resulting circuit demonstrates that it operates as a ring attractor. Fig 4 shows an example of the neural activity of the simulated circuit with the activity 'bump' transitioning from one attractor state to another in response to changing of the stimulus azimuth by 180^o.

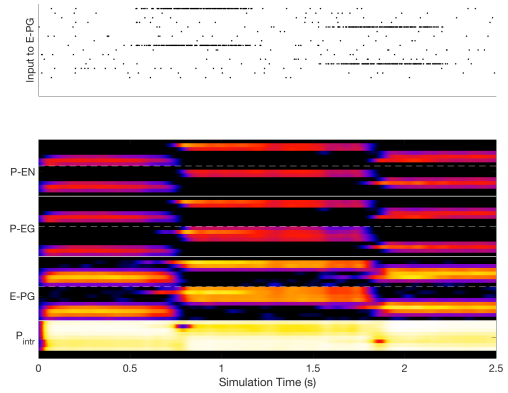

Figure 4: Response of the ring attractor to abrupt changes of stimulus azimuth position.

The top of Fig 4 shows the stimulus provided to the ring attractor circuit during the simulation. The initial stimulus spiking activity sets the ring attractor to an initial attractor state. A 'darkness' period of no activity follows, during which the bump of activity is maintained in the same location. Then a second stimulus, corresponding to a sudden change of heading by 180^o, is provided, producing a rapid change in the position of the bump, with this new location then maintained after the stimulus is removed. The activity of each neuron is shown at the bottom of the image with colour encoding the spiking rate. In Fig 4 there are two peaks of activity for each neuron type because neurons from each EB wedge innervate both the left and the right hemisphere of the PB.

4 Conclusions

The increasing availability of detailed circuit structure, particularly in invertebrate brains, raises the possibility to simulate complete circuits. However, while directly implementing and running a model with the known connectivity of a biological neural circuit has

the potential to inform us about the computation performed by the circuit and possibly to derive a transfer function, it does not necessarily provide real understanding of the principle of function that the circuit embodies. Reverse engineering of the neural circuit connectivity is necessary for understanding the underlying principles of the computational structure and for facilitating efficient transfer to technology.

Here, as an example, we have reverse engineered the circuit that is reportedly encoding the current heading direction of the fruit fly *Drosophila melanogaster*. We derive the equivalent network topology and then determine (through optimisation) the synaptic strengths that would allow it to operate as a ring attractor mimicking the dynamics of the biological structure. We note that this also allows us to make predictions about the synaptic strengths in the biological circuit, which have yet to be measured.

We found that this circuit has an eight-fold symmetry and that is able to operate as a ring attractor maintaining a 'bump' of activity that corresponds to the heading of the latest applied stimulus. The effective circuit resembles the ring attractor proposed by Skaggs et al. (1995) with some structural differences. The $\Delta 7$ neurons provide global, uniform, inhibition. The E-PG and P-EN neurons compose the core of the excitatory circuit. The P-EG neurons are a novel element in a ring attractor. These neurons are part of local feedback loops within each octant of the circuit. We suggest that these neurons increase the tolerance of the circuit to noise and asymmetries of the synaptic strengths hence reducing the drift of the 'bump' of activity.

Another difference from the traditional ring attractor circuits is that the P-EN neurons that assume the role of shifting the 'bump' of activity left or right around the circuit, when stimulated externally, are part of the excitatory circuit instead of functioning as mere input neurons. In *Drosophila melanogaster* it has been shown that when the P-EN neurons innervating one hemisphere of the PB are stimulated, the activity 'bump' shifts contralaterally. This suggests a more efficient use of neural resources when compared with typical ring attractor models.

These identified differences can inspire the design of novel ring attractor architectures for neurorobotics with increased stability and efficiency of neural resources usage. This mechanism appears to be a particularly effective means for an animal to internally track its orientation with respect to its surroundings and in insects appears to be a core component of a range of navigational behaviours from long range migration to local path integration. The continued study of the detailed anatomy of the insect brain provides an exciting opportunity for the further unravelling of the circuit function that supports complex adaptive behaviour.

References

Shun-ichi Amari. Dynamics of pattern formation in lateral-inhibition type neural fields. *Biological Cybernetics*, 27(2):77–87, 1977.

Alex J. Cope, Chelsea Sabo, Eleni Vasilaki, Andrew B. Barron, and James A.R. Marshall. A computational model of the integration of landmarks and motion in the insect central complex. *PLoS ONE*, 12(2): e0172325, 2017.

Ysabel Milton Giraldo, Katherine J. Leitch, Ivo G. Ros, Timothy L. Warren, Peter T. Weir, and Michael H. Dickinson. Sun Navigation Requires Compass Neurons in Drosophila. *Current Biology*, 28(17):2845–2852.e4, 2018.

Jonathan Green, Atsuko Adachi, Kunal K. Shah, Jonathan D. Hirokawa, Pablo S. Magani, and Gaby Maimon. A neural circuit architecture for angular integration in Drosophila. *Nature*, 546(7656):101–106, 2017.

Stanley Heinze and Uwe Homberg. Maplike Representation of Celestial E-Vector Orientations in the Brain of an Insect. *Science*, 315(5814):995–997, 2007.

Stanley Heinze and Uwe Homberg. Neuroarchitecture of the central complex of the desert locust: Intrinsic and columnar neurons. *Journal of Comparative Neurology*, 511(4):454–478, 2008.

Uwe Homberg, Stanley Heinze, Keram Pfeiffer, Michiyo Kinoshita, and Basil El Jundi. Central neural coding of sky polarization in insects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1565):680–687, 2011.

Kyobi S. Kakaria and Benjamin L. de Bivort. Ring Attractor Dynamics Emerge from a Spiking Model of the Entire Protocerebral Bridge. *Frontiers in Behavioral Neuroscience*, 11:8, 2017.

Sung Soo Kim, Hervé Rouault, Shaul Druckmann, and Vivek Jayaraman. Ring attractor dynamics in the Drosophila central brain. *Science*, 356(6340):849–853, 2017.

Gang Liu, Holger Seiler, Ai Wen, Troy Zars, Kei Ito, Reinhard Wolf, Martin Heisenberg, and Li Liu. Distinct memory traces for two visual features in the Drosophila brain. *Nature*, 439(7076):551–556, 2006.

Kirsa Neuser, Tilman Triphan, Markus Mronz, Burkhard Poeck, and Roland Strauss. Analysis of a spatial orientation memory in Drosophila. *Nature*, 453(7199):1244–1247, 2008.

Tyler A. Ofstad, Charles S. Zuker, and Michael B. Reiser. Visual place learning in Drosophila melanogaster. *Nature*, 474(7350):204–209, 2011.

Keram Pfeiffer and Uwe Homberg. Organization and Functional Roles of the Central Complex in the Insect Brain. *Annual Review of Entomology*, 59(1): 165–184, 2013.

Roy E. Ritzmann, Cynthia M. Harley, Kathryn A. Daltorio, Brian R. Tietz, Alan J. Pollack, John A. Bender, Peiyuan Guo, Audra L. Horomanski, Nicholas D. Kathman, Claudia Nieuwoudt, Amy E. Brown, and Roger D. Quinn. Deciding Which Way to Go: How Do Insects Alter Movements to Negotiate Barriers? *Frontiers in Neuroscience*, 6:97, jul 2012. ISSN 1662-4548. doi: 10.3389/fnins.2012.00097.

Johannes D. Seelig and Vivek Jayaraman. Neural dynamics for landmark orientation and angular path integration. *Nature*, 521(7551):186–191, 2015.

W E Skaggs, J J Knierim, H S Kudrimoti, and B L McNaughton. A model of the neural basis of the rat's sense of direction. *Advances in neural information processing systems*, 7(1984):173–80, 1995.

R.B. B. Stein. Some Models of Neuronal Variability. *Biophysical Journal*, 7(1):37–68, 1967.

Thomas Stone, Barbara Webb, Andrea Adden, Nicolai Ben Weddig, Anna Honkanen, Rachel Templin, William Wcislo, Luca Scimeca, Eric Warrant, and Stanley Heinze. An Anatomically Constrained Model for Path Integration in the Bee Brain. *Current Biology*, 27(20):3069–3085.e11, 2017.

Roland Strauss. The central complex and the genetic dissection of locomotor behaviour. *Current Opinion in Neurobiology*, 12(6):633–638, 2002.

Ta Shun Su, Wan Ju Lee, Yu Chi Huang, Cheng Te Wang, and Chung Chuan Lo. Coupled symmetric and asymmetric circuits underlying spatial orientation in fruit flies. *Nature Communications*, 8(1), 2017.

JS Taube, RU Muller, and JB Ranck. Head-direction cells recorded from the postsubiculum in freely moving rats. I. Description and quantitative analysis. *The Journal of Neuroscience*, 10(2):420–435, 1990.

Tilman Triphan, Burkhard Poeck, Kirsa Neuser, and Roland Strauss. Visual Targeting of Motor Actions in Climbing Drosophila. *Current Biology*, 20(7):663–668, 2010.

Daniel Turner-Evans, Stephanie Wegener, Hervé Rouault, Romain Franconville, Tanya Wolff, Johannes D Seelig, Shaul Druckmann, and Vivek Jayaraman. Angular velocity integration in a fly heading circuit. *eLife*, 6:2112–2126, 2017.

Tanya Wolff and Gerald M. Rubin. Neuroarchitecture of the Drosophila central complex: A catalog of nodulus and asymmetrical body neurons and a revision of the protocerebral bridge catalog. *Journal of Comparative Neurology*, 526(16):2585–2611, 2018.

Tanya Wolff, Nirmala A. Iyer, and Gerald M. Rubin. Neuroarchitecture and neuroanatomy of the Drosophila central complex: A GAL4-based dissection of protocerebral bridge neurons and circuits. *Journal of Comparative Neurology*, 523(7): 997–1037, 2015.

J. M. Young and J. D. Armstrong. Structure of the adult central complex in Drosophila: Organization of distinct neuronal subsets. *Journal of Comparative Neurology*, 518(9):1500–1524, 2010.

K Zhang. Representation of spatial orientation by the intrinsic dynamics of the head-direction cell ensemble: a theory. *The Journal of Neuroscience*, 16(6): 2112–2126, 1996.