Sexual dimorphism in the complete connectome of the *Drosophila* male central nervous system

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Abstract

Sex differences in behaviour exist across the animal kingdom, typically under strong genetic regulation. In *Drosophila*, previous work has shown that *fruitless* and *doublesex* transcription factors identify neurons driving sexually dimorphic behaviour. However, the organisation of dimorphic neurons into functional circuits remains unclear.

We now present the connectome of the entire *Drosophila* male central nervous system. This contains 166,691 neurons spanning the brain and ventral nerve cord, fully proofread and comprehensively annotated including *fruitless* and *doublesex* expression and 11,691 cell types. By comparison with a previous female brain connectome, we provide the first comprehensive description of the differences between male and female brains to synaptic resolution. Of 7,319 cross-matched cell types in the central brain, 114 are dimorphic with an additional 262 male- and 69 female-specific (totalling 4.8% of neurons in males and 2.4% in females).

This resource enables analysis of full sensory-to-motor circuits underlying complex behaviours as well as the impact of dimorphic elements. Sex-specific and dimorphic neurons are concentrated in higher brain centres while the sensory and motor periphery are largely isomorphic. Within higher centres, male-specific connections are organised into hotspots defined by male-specific neurons or the presence of male-specific arbours on neurons that are otherwise similar between sexes. Numerous circuit switches reroute sensory information to form conserved, antagonistic circuits controlling opposing behaviours.

Introduction

A fundamental goal of neuroscience is to connect the structure and function of neural circuits to behaviour. To understand how brains transform sensory information and memories into motor actions, we must determine the component parts of neural circuits, understand how they fit together, and investigate the functional consequences of manipulating specific circuit elements. Sexual dimorphisms provide a natural experimental framework for causal inference: when the same sensory stimulus evokes different behaviours in males and females of a species, dissecting the underlying neural circuits offers insights into how the brain produces behaviour. For example, virgin male and female mice respond differently to the presence of pups: while females parent, males are infanticidal. These antagonistic behaviours are controlled by a sexually dimorphic population of inhibitory neurons in the medial amygdala[1]. While this and other studies in rodents[2–8] have identified brain regions and broad cell populations implicated in promoting dimorphic behaviours, mapping the entire underlying circuit architecture remains intractable in such a numerically complex model system.

The adult fruit fly *Drosophila melanogaster* represents a powerful model for studying sexual dimorphism at the levels of genes, circuits, and behaviour. Sexually dimorphic behaviours such as courtship and aggression depend on complex sensorimotor integration. Although genetically specified by the transcription factors *fruitless* and *doublesex*[9–11], they can be modified by experience[12]. Powerful molecular genetic toolkits have enabled access to specific cell types within broad *fruitless* and *doublesex*-expressing neuronal populations,

making it possible to dissect their contributions to numerous sexually dimorphic behaviours[13–17].

Until now, studies of sexual dimorphism in *Drosophila* have focused on the impact of individual cell types on physiology and behaviour[18–20]. For example, male-specific P1 neurons, a diverse population which express *doublesex* and in some cases also *fruitless*, promote courtship song[19,21–23] and aggression[24]. P1 neurons appear to be a key node controlling sex-specific behaviour with strong parallels to mammals[25], but the circuit architecture that allows them to promote mutually exclusive behaviours remains elusive. In a few other cases it has been possible to pinpoint circuit nodes that redirect sensory information to opposing downstream circuitry[26,27] but this remains the exception.

Whole-brain connectomics provides a systematic approach to address this circuit gap by placing individual neurons into complete synaptic resolution circuits. Connectomics has already proven useful for investigating neural circuit mechanisms of a range of complex behaviours in *Drosophila*[28] even including cognitive processes that are individual to an organism or dynamic such as memory or the interaction between visual attention and internal state[29]. Connectomes of the fly brain and nerve cord have recently become available[30–35], enabling dissection of neural circuits with single-neuron resolution.

Building on this foundation, we present the first finished connectome of an entire male *Drosophila* central nervous system. This work provides two critical advances (1) a fully proofread and annotated brain and nerve cord connectome with an intact neck connective; and (2) the first example of a male brain. Leveraging existing female connectomes, this resource enables the first brainwide, synaptic-resolution comparison across sexes of an adult animal with complex anatomy and behaviour. We identify 331 sex-specific and 114 sexually dimorphic cell types, comprising 4.8% of the male and 2.4% of the female central brain. We found a high correspondence between dimorphism status and *fruitless*/*doublesex* expression, but these are not completely overlapping. Sex-specific and dimorphic neurons are concentrated in higher order brain centres while the sensory and motor periphery are largely isomorphic. Although only a small fraction of all neurons, dimorphism propagates through the nervous system via dimorphic connectivity, suggesting that even modest changes in circuitry can exert brain-wide influence. Comparative connectomics of circuits for a number of sensory and behavioural modules uncovers general principles of the neural architecture for sex-shared, sex-specific, and flexible behaviours. This resource enables exploration of neural circuits spanning the entire CNS and comparison of these circuits across sexes to elucidate the circuit-level impact of sexual dimorphism.

Results

A complete connectome of a whole male CNS

Here we present the fully proofread connectome of the central nervous system (CNS) of an adult *Drosophila melanogaster* male, extending the right optic lobe connectome previously reported in Nern *et al.*[36]. Using 7 focused ion beam milling and serial electron microscopes (FIB-SEM)[37] over 13 months, we generated an image volume of 160 teravoxels (excluding empty regions) at 8x8x8 nm isotropic resolution (0.082 mm^3 in total, of which 0.054 mm^3 is

occupied by tissue) encompassing the central brain, optic lobes, and ventral nerve cord (VNC, insect spinal cord analogue) (Fig 1a). The volume was aligned and segmented with flood filling networks[38] to reconstruct neurons. Synaptic connections were automatically predicted using two separate neural networks: one for presynaptic T-bars, and one for postsynaptic densities (PSDs). This detected 46 million presynapses connected to 312 million PSDs across the entire volume with an average precision/recall for connections of 0.82/0.81 respectively (Extended Data Fig 1i). We further extracted a number of additional features, including nuclei and neurotransmitter predictions[39].

The initial neuron segmentation was proofread over 3 years by 29 expert proofreaders (estimated effort of 44 person-years), using a variety of bottom-up (e.g. backbone tracing) and top-down (e.g. left/right symmetry checks) workflows (Extended Data Fig 9f). In total, we identified, proofread and annotated 166,691 neurons (including sensory axons) across the entire volume (Fig 1b). While absolute certainty is difficult to achieve in datasets as large as this, we are confident that these numbers represent the entirety of traceable neurons. First, 98.9% of the 141,780 detected neuron-associated nuclei are part of a proofread neuron. Second, we proofread all fragments from the initial segmentation with at least 100 synaptic connections. After proofreading, only 0.6% of neurons with attached soma are composed entirely of fragments below this threshold. Thus, for the 1.1% of nuclei which remain unassociated with proofread arbours, we estimate that > 99% of the corresponding neurons have been proofread but have not been connected to their cognate nucleus in the cell body rind on the outside of the brain. Third, the resulting neuron counts match those reported for existing brain and VNC connectomes (Fig 1e). For sensory neurons (without a cell body in the dataset), we seeded and traced axon profiles in all nerves entering the volume. Only a small number of cells could not be reconstructed due to sample artefacts on the edge of the volume (e.g. some R1-6 photoreceptors neurons in the laminae) or segmentation issues (e.g. some sensory neurons and motor neurons) (see Methods for details).

The traditional metric for estimating the completeness of the connectome's wiring diagram is the fraction of pre- and postsynapses associated with a proofread neuron. With 94% pre- and 42% postsynaptic completion rates in neuropils, this dataset is similar to or exceeds previously published connectomes[30–34] (Fig 1c, Extended Data Fig 9g). Going forwards we suggest that the fraction of synaptic connections for which both pre- and postsynaptic sites belong to a proofread neuron is a more useful metric. For the neuropils of the male CNS connectome, that fraction is 40.1% (Fig 1d).

To maximise this dataset's utility for the wider biological community, we provide comprehensive annotations detailing the organization and structure of the entire *Drosophila* central nervous system. These are informed by and cross-referenced with recent partial connectome datasets. The coarsest annotation, "`superclass`", describes the direction of information flow, anatomical location and broad function of neurons. At the most granular level, we identify terminal cell types based on morphological and connectivity properties of individual neurons. We identified 11,691 unique cell types across the optic lobes, central brain and VNC. Orthogonal annotations include information about developmental origin, spatial location (`somaSide`, `somaNeuromere`, `entry/exitNerve`), putative function (`class` and `subclass`) and names used in the literature (`synonyms`) (Fig 1f and Extended Data Fig 1c).

To enable across-dataset comparisons, we used quantitative metrics of morphology (NBLAST[40]) and connectivity similarity to systematically match and annotate cell types across existing connectomes (see Methods for details) (Fig 1h,i). This matching is largely complete, with 97.5% of neurons across the CNS having a cell type match to either the FAFB/FlyWire[30,31,41], hemibrain[32] and/or the male adult nerve cord (MANC)[32–34] dataset (Fig 1h and Extended Data Fig 1e). Breaking this down further, we cross-matched 96.4% of central brain and 98.8% of optic lobe neurons to FAFB/FlyWire and/or hemibrain datasets, and 93.1% of VNC neurons to MANC (Fig 1h). We were unable to match a fraction of efferent (15%) and sensory (15%) neurons in the VNC due to limitations in data quality and intrinsic variability which was not well-captured in cell typing in previous datasets. In addition, while ascending neurons could be confidently matched between male CNS and the previous MANC nerve cord connectome, around one third of these neurons could not be matched with the FAFB/FlyWire brain connectome since their arbours in the brain are too small for confident matching. Similar issues prevented confident matching of 29% of sensory ascending neurons that project from VNC to brain with the MANC dataset – reliable identification requires analysis of both brain and VNC (Extended Data Fig 1f). Neurons not matched due to sexual dimorphism (i.e. male-specific neurons) are discussed in detail later.

While we were able to match cell types across connectomes with high fidelity, nomenclature is not yet always consistent. We therefore recorded parallel type annotations for other datasets (`mancType`, `flywireType`, `hemibrainType`) so that the corpus of male CNS annotations now serve as a connectomic rosetta stone. In the process of cross-matching neurons, we occasionally revised existing cell types in FAFB/FlyWire, hemibrain and/or MANC when whole-CNS information enabled more accurate cell typing (see Methods for downloadable resources). Reassuringly, we do see that cell type definitions are converging: we revised about 4% of FlyWire neurons in this work (Extended Data Fig 1h) whereas in earlier work matching the hemibrain to FlyWire we had to revise over 44% of cell types[31]. The process of integrating this most complete dataset with earlier *Drosophila* connectomes has therefore allowed cell type boundaries to be refined to create a more accurate and durable consensus cell type atlas.

Taken together, we anticipate that this high quality and extensively annotated connectome will be the principal reference for researchers exploring the anatomy, connectivity, and development across the *Drosophila* CNS, and for unraveling the structure-function relationships linking circuits to behaviour. We provide a landing page that brings together the various resources (images, segmentation, neuron reconstructions, connectome graph, neurotransmitter predictions, annotations, etc.), including ways to interactively explore cell types, connectivity and male-female dimorphism, and raw data for download (see also Methods).

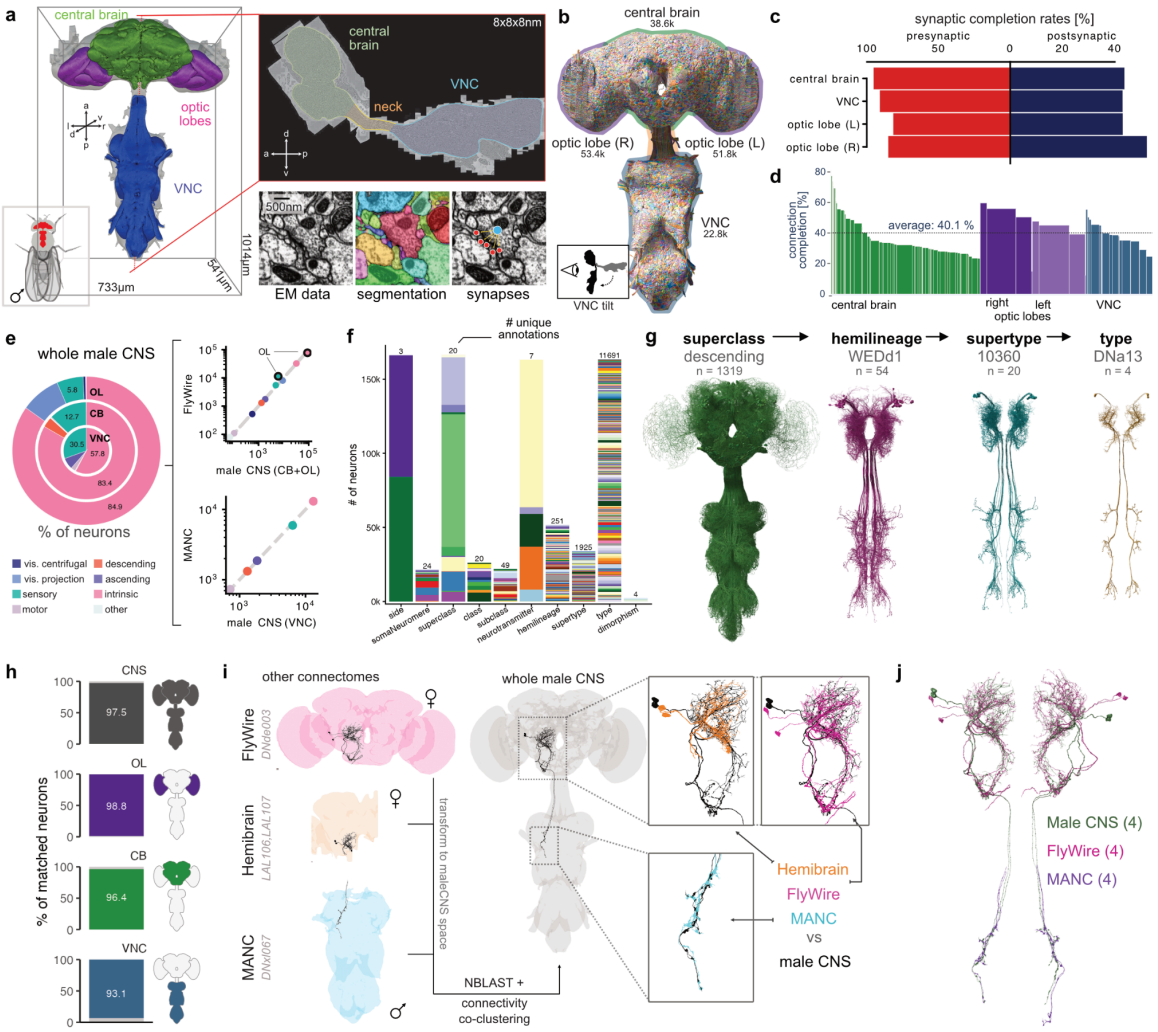

Figure 1 | A densely annotated and cross-matched male CNS connectome

a Outlines of the aligned male CNS volume, coloured by CNS region (left). Sagittal slice through the EM image data (top right). Insets show (from left): image data, neuron segmentation, and synapse detection. **b** 3D rendering of all neurons in the connectome. Frontal view; VNC tilted down for visualisation. Numbers represent neuron counts per brain region, including sensory neurons. **c** Synaptic completion rates for pre- and postsynapses per brain region. **d** Percentage of connections where both pre- and postsynaptic partners are proofread broken down by neuropil region. Bar width corresponds to size of neuropil. **e** Percentages of neurons for main superclasses across brain regions (left). Comparison of neuron counts to existing connectomes: female brain (FAFB/FlyWire, top right) and male nerve cord (MANC, bottom right). **f** Number of neurons per annotation field. The number of unique annotations for each field is shown at the top of the bar. `side` combines fields `somaSide` and `rootSide`; `hemilineage` combines fields `itoleeHl` and `trumanHl`. **g** Example for the hierarchical annotation of neurons, from superclass through hemilineage, supertype and type. The annotation and the number of neurons in that category is shown in grey. **h** Percentage of neurons matched to an existing dataset in the whole CNS and for each CNS region. **i** Neurons were matched to existing connectomes using a combination of spatial transforms + NBLAST and connectivity co-clustering. Example shown here is DNde003, a descending neuron type, with a 1:1 match in FlyWire and MANC, and matched to two types in hemibrain. **j** Full view of DNde003 in male CNS, FlyWire and MANC. The number of neurons in each dataset is shown in brackets. EM:

electron microscopy; OL, optic lobes; CB, central brain; MANC: male adult nerve cord connectome; VNC: ventral nerve cord.

Information flow from sensory to motor

Using a limited repertoire of sensors (sensory neurons) and effectors (motor neurons), flies flexibly perform complex behaviours such as navigation, aggression, and courtship[23,42–46]. We comprehensively mapped sensory and motor neurons across the brain and nerve cord (Fig 2a and Extended Data Fig 2a). Detailed annotations for the entry nerve, modality, and receptor subtype of sensory neurons, such as SNpp32 (`superclass`: `vnc_sensory` → `class`: `mechanosensory_proprioceptive` → `subclass`: `campaniform sensilla` → `type`: `SNpp32`) and the exit nerve and muscular innervation of motor neurons like CvN7 (`superclass`: `cb_motor` → `subclass`: `nm` (neck motor) → `type`: `CvN7`) are available (Fig 2b). Combining these annotations with the intact whole-CNS connectome, we can investigate full sensory-to-motor circuits.

We can obtain a bird's eye view of the connectome by considering only connections between superclasses (Fig 2c). This shows information primarily traversing the CNS in a feedforward manner from sensory inputs to motor output. Sensory information from the head and body enters via brain and VNC nerves, respectively, and exits primarily via motor neurons in the VNC. Synaptic connections in this feedforward direction have similar compositions of neurotransmitters and are predominantly excitatory, while feedback connections have a larger inhibitory proportion. The neck connective is a key bottleneck in this flow of information, where descending neurons constrain information traveling from the brain to the VNC, and ascending neurons constrain flow in the opposite direction. However, neck connective neurons are not only simple relays spatially bridging the two main divisions of the CNS. For example, ascending neurons output a similar number of synapses as descending neurons onto VNC-intrinsic neurons while also receiving more information from VNC-intrinsic neurons than from direct sensory inputs. Neck connective neurons also participate in the majority of feedback connections in this sensory-to-motor orientation. In the rest of this section, we examine the organization of sensory-to-motor information flow in the neck connective.

Unlike prior datasets spanning only the brain or VNC, an intact whole-CNS connectome allows all neurons and circuits to be contextualized with respect to their role in information flow from sensors to effectors. To investigate, we employed maximum flow analysis, a commonly used network analysis technique[47]. In brief, this finds the greatest possible rate at which information can move through the network from a source to a destination without exceeding capacity limits of the connections (here set by the synaptic weights between neurons). By systematically redistributing flow across alternative routes, the analysis identifies bottlenecks and the overall throughput limit of the network. Compared with the alternatives, maximum flow is better able to reveal long range information flow and can yield distinct measures for each source and sink pairing; however it chooses a single path (so negative inferences should be made with caution) and like most methods does not leverage the sign of connections.

Specifically, we used maximum flow analysis originating from all sensory neurons of a particular modality `class` (as a group), and terminating at motor neurons from each motor domain `subclass` (Fig 2a,d). This analysis was performed for all pairs of sensory modalities and motor domains on a presynaptic-input-normalized connectome graph, recording the resulting flow over all neuron-to-neuron edges and neuronal nodes. For example, DNp44 descending neurons have high maximum flow to many motor domains from olfactory and hygrosensory neurons, indicating they may prefer information flow from these modalities (Fig 2f). In the strong flow path from olfaction to the front leg motor domain (Fig 2e), DNp44's strongest upstream flow contributors are VP4 thermohygrosensory projection neurons known to be dry air sensing[48]. Upstream of these, the strongest flow originates from olfactory receptor neurons including several associated with aversive odorants (DP1, DL5), passing through interneurons including GABAergic inhibition. Thus DNp44 carries hygrosensory information, which may be gated by olfactory information.

Examining sensory-motor flow over the entire CNS highlights the distinct role of neck connective neurons in information processing. First, ascending and descending neurons have a much higher flow utilization (i.e. the mean percentage of their synaptic capacity utilized across all sensory-motor flows) than brain- and VNC-intrinsic neurons, indicative of their role as information bottlenecks (Fig 2g, left). Second, these flows are more specific towards particular motor domains (e.g. front or hind legs) than they are towards particular sensory modalities (e.g. gustation or thermosensation). This trend consolidates in the VNC, where circuits are more segregated as they fan out to control particular effectors (Fig 2g, middle). Third, while intrinsic neurons of both the brain and VNC are on average more specific to particular sensorimotor pairings, ascending and descending neurons tend to be specific for a particular sensory modality or a particular motor domain, but not both (Fig 2g, right, Extended Data Fig 2b). In other words, neck connective neurons are multimodal (either in sensory or motor space); we propose that this lower specificity relative to other CNS neurons is driven by the joint constraints of the information bottleneck and the complex behaviours these neurons must orchestrate.

To better understand this multimodal structure within the neck connective, we clustered all descending and ascending neurons on the basis of an embedding of their sensorimotor flow (Fig 2h). While some clusters are predominantly composed of only ascending or descending neurons, or have high specificity to a single sensory modality or motor domain, many are more heterogeneous (Fig 2i). Neck connective neuron types whose function has been described in previous literature were sorted into broad behavioral categories. Clusters containing many described types favor a single behavioral category (Fig 2j, top), demonstrating the functional salience of the flow analysis. To assess this flow analysis as an aid for behavioral function hypothesis, we created simple rules defining which sensory-motor pairings are potentially compatible with which behavioral categories (Fig 2j, bottom), see methods). In most cases, clusters with many described neurons have the described behavioral category ranked as highly compatible based on their sensory-motor flow (receiver operating characteristic area under curve 0.84 when compatibility is treated as a multilabel classifier of described behavioral category). Clusters also structure connectivity between ascending and descending neurons (Extended Data Fig 2c), which could previously only be analyzed via an incomplete matching of cell types across multiple partial connectome datasets from different animals [49].

For a more granular understanding of how connectivity between neck connective neurons relates to information flow and connectivity with other populations, we analyzed type to type connections within and between ascending neurons (AN) and descending neurons (DN) (Fig 2k). There are few strongly connected types for each of the four superclass pairings. DN-DN and AN-DN synapses are predominantly in the brain, while AN-AN and DN-AN synapses are predominantly in the VNC. For AN-DN and DN-AN pairings, this is consistent with an expectation of axo-dendritic connectivity and archetypical localization of arbours from these superclasses. While we observe that connectivity is predominantly axo-dendritic in all three cases, a larger proportion of connectivity within DNs (27%) and ANs (34%) is dendro-dendritic than for the other two cases (both 4%) (Fig 2l).

Strongly connected descending types DNb07 and DNp63 (cluster 11) are exemplary of how connectivity within the neck connective population is organized by shared sensory-motor information flow (Fig 2m). While both types project similar axonal arbours in the VNC, they form distinct dendritic arbours in the brain. Their interconnection is 91% axo-axonic, with glutamatergic DNb07 synapsing onto cholinergic DNp63 in both the brain and VNC, an inhibitory motif. 30% of their downstream partners are shared, yet they share only one strong (> 20 synapses) upstream partner: glutamatergic ascending neuron type AN27X015 (cluster 14). Despite the lack of common presynaptic partners, both DN types have similar flow (cosine similarity 0.93), preferring olfactory and visual modalities, with flows towards the legs, abdominal effectors, and wings (Extended Data Fig 2d). AN27X015 projects back from the VNC axonal domain of DNb07 and DNp63 to their brain dendrites, but is preferential for mechanosensory (tactile & proprioceptive) modalities and proboscis and abdominal motor domains. In summary, these three cell types form a motif where sensory information from the same domains flows through distinct pathways and converges onto overlapping circuitry via DNs expressing different neurotransmitters. Nearby ascending feedback contributes information from distinct sensory modalities to this circuit. That a multisensory motif of this complexity can be identified and a convergent, inhibitory function hypothesized solely from network analysis, despite none of the three types involved having previously been functionally described in the literature, demonstrates the utility of an intact CNS dataset of this quality as a resource.

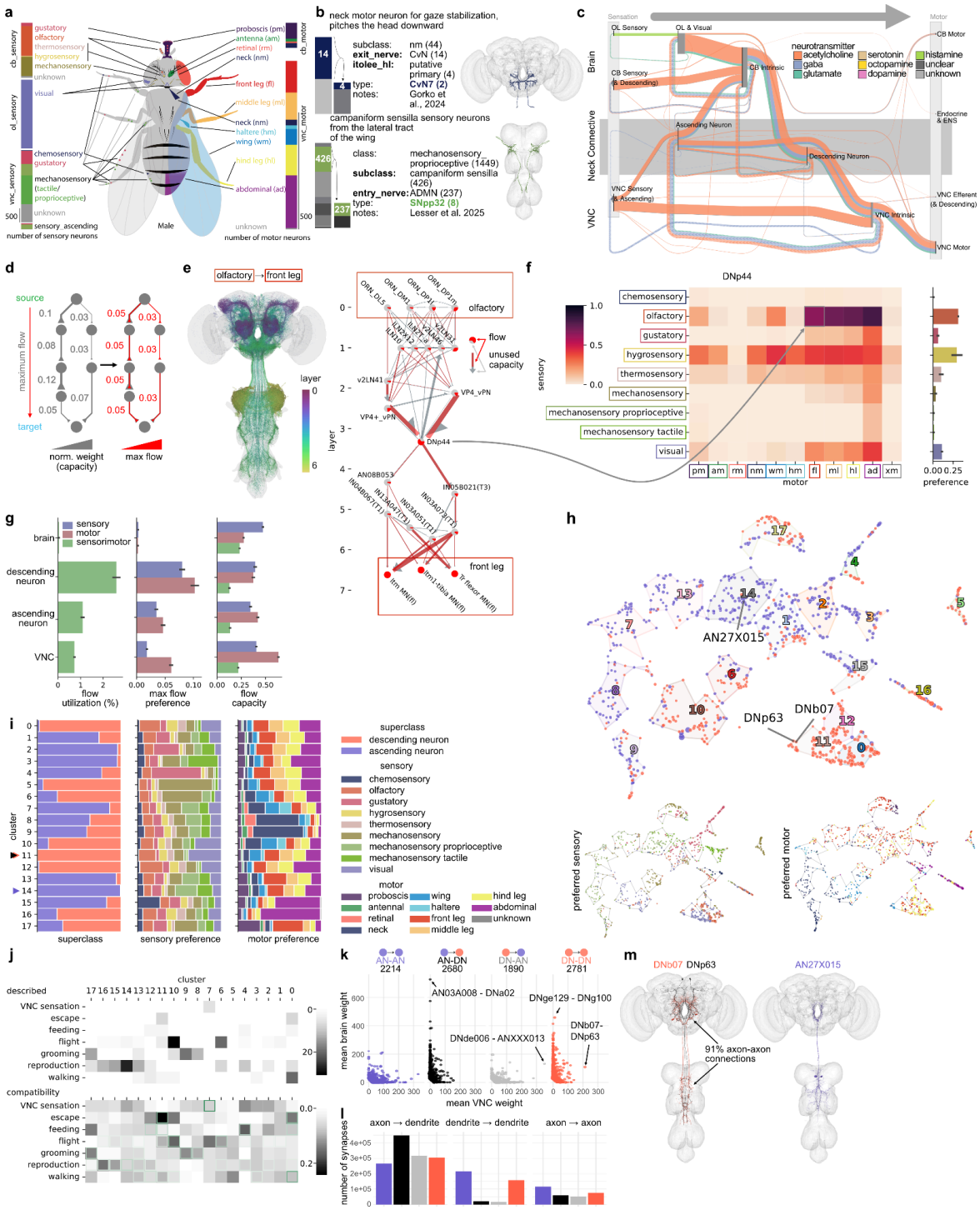

Figure 2 | Information flow from sensory input to motor output organizes circuits spanning brain and nerve cord

a Schematic of sensory groups (by class) and motor group (by subclass). Bars show the number of neurons belonging to each group. Lines indicate where the neuron is projecting from or to. White asterisk indicate the examples shown in (b). **b** Example of detailed annotation available for sensory neurons and motor neurons. Top: morphology of neck motor neuron type CvN7. Stacked bar for exit nerve and hemilineage (`itoleeHl`). Bottom: wing campaniform sensilla sensory type SNpp32 in the VNC. Stacked bar for subclass and entry nerve. **c** Directed flow diagram of synaptic

connections from sensory to motor through the entire CNS. Colours correspond to predicted neurotransmitter identity, right-to-left connections are shown as hash lines. Edge width is proportional to the number of intergroup synapses, node width is proportional to the number of intrinsic intragroup synapses. Edges with fewer than 20k synapses omitted. **d** Schematic of maxflow analysis. Left: normalized edge weights establish potential capacities of information flow between each node. Right: maxflow assignment of flow value across each edge, illustrating flow constrained by the minimum capacity along a path. **e** Example of maxflow path from olfactory sensory inputs to front leg motor outputs. Left: neurons (flow value > 0.25) colored according to their pseudo-layer ordering. Right: strong flow partners (by type) upstream and downstream of example neurons in type DNp44. Arrow to (f) indicates where the flow for this sensory-motor pairing fills in DNp44's overall sensory-to-motor flow matrix. **f** Example of mean maxflow through neurons in type DNp44 (left) and sensory modality preference averaged from flow (right). **g** Flow for neck connective neurons. Proportion of flow utilization of different superclasses (left) and flow specificity for one sensory group, motor group or a single sensory to motor group (right). **h** UMAP embedding of DN and AN types by sensorimotor flow, coloured by superclass and sized by presynaptic sites, outlined by numbered clusters (left). Types shown in (m) are annotated. Right top: coloured by preferred sensory modality, sized by maximum sensory preference value. Right bottom: same as the above for motor preference. **i** Composition of superclass and preferred sensory modalities and motor domains for clusters in (h). Arrows indicate clusters containing types in (m). **j** Behavioral categorization of clusters. Top: histogram of cluster membership of neck connective types described in literature by behavior category. Bottom: compatibility of clusters with behavior categories as predicted based on maxflow analysis. Frequency of descriptions from top panel are overlaid in green. **k** Connection pairs of neck connective types by superclass with mean weight above 20. Plotted by strength of connection in the brain and VNC. Arrows highlight examples of strong connections. Numbers above show type-type connections for each motif. **l** Axon-dendrite split of DNs and ANs shows the type of connections made by pairs between these superclasses. Only the three most prominent types of connections are shown: axon to dendrite, dendrite to dendrite, axon to axon. **m** Example of a strong DN to DN connection that is 91% axo-axonic. The only common target in the brain is AN27X015.

Identifying sexually dimorphic circuit elements

Sex differences in behaviour are thought to arise from a combination of unique circuit elements, sex-specific circuit wiring and sex-dependent physiological properties of cells[26,50–52]. Connectomics enables comparison of all structural differences in the nervous system at synaptic resolution. Here we compare this male dataset and female brain connectomes (FAFB/FlyWire and hemibrain), assessing the extent to which sexual dimorphisms in the brain primarily reflect differences in neuronal cell types or in connections between shared circuit elements, and relate these differences to molecular mechanisms of sex differentiation.

Cell types (most of which consist of multiple neurons in the adult fly), represent the fundamental unit of conservation across brains and brain hemispheres[31,53,54]. We assigned a type match for 96.4% of neurons in the male CNS brain and 98.8% of the optic lobe with one or both female brain datasets (Fig 1h, Extended Data Fig 1e). Cross-matched neurons include both iso- and dimorphic neurons. Neurons that remained unmatched were candidates for sex-specific types. To assign dimorphism labels, we operationally defined isomorphic, sex-specific and sexually dimorphic cell types using the criteria listed in Table 1 and illustrated by Fig 3a. These definitions are focussed on neurons that exhibit clear

morphological differences between the sexes. We will investigate "secondarily dimorphic" neurons that are morphologically isomorphic but still exhibit dimorphic connectivity later in the results. Due to the absence of a fully-proofread female VNC connectome for comparison, we relied and expanded on dimorphism labels from previous literature describing the VNC[27,55–60] especially the recent work of Stürner *et al.*[49] (see Methods for details).

Table 1: Definitions of dimorphism

Isomorphic	Sexually dimorphic	Sex-specific
A group of neurons consisting of approximately equal numbers from all four hemispheres (male left, male right, female left, female right). Neurons share the same overall morphology and connectivity, and typically intermingle in either a dendrogram or low-dimensional embedding (UMAP, see Methods for details) (Fig 3a,c; Extended Data Fig 3b). Individual members can exhibit slight variations in morphology (such as additional small or medium-sized branches) and/or connectivity, but the differences are not consistent across hemispheres. This left/right symmetry is required to filter out both biological variability and technical noise.	A group of neurons with shared developmental origin consisting of both male and female neurons from all four hemispheres. Neuron counts can differ between sexes but must be approximately equal between hemispheres from the same sex. Neurons must exhibit clear and consistent morphological differences (e.g. extra branches or shifted dendrites) between sexes which must result in changes in connectivity. The latter requirement is to avoid cases where neurons have atypical morphology (e.g. projecting through a different axon tract) but ultimately connect to the same synaptic partners. Sexually dimorphic neurons typically separate by sex in a dendrogram or low-dimensional embedding but are still each other's closest match (Fig 3a,d; Extended Data Fig 3d). We provide explanations of the nature of the differences in the `matching notes` field.	Unmatched groups of neurons from both hemispheres of one sex, where the closest group of neurons from the other sex has already been assigned a better isomorphic or dimorphic match (Fig 3a,e; Extended Data Fig 3c). In some instances the distance between a large dimorphic group of male and female neurons is too big to match terminal cell types one-to-one (e.g. AVLP727m). In that case, individual cell types were labeled as sex-specific but are still linked through a common `supertype` (or in some cases, `synonym` or `matching notes`) assigned to all members of that group.

Applying these criteria, we identified 1,427 male-specific neurons across both hemispheres of the male CNS (vs 363 female-specific) and 924 dimorphic neurons (matched with 811 neurons in the female) (Fig 3b). Differences in dimorphic neuron counts between male and female originate primarily in the optic lobes and the VNC. For the optic lobes, this is the result of a higher number of visual columns in the male specimen (male ~900; female ~800) leading to higher counts for numerous, repeated cell types; this is unlikely to be a systematic difference between the sexes[36]. For the VNC, our annotations in the male include 15 dimorphic types (47 neurons) from previous publications[49] that are either VNC-intrinsic (i.e. do not have a correlate in the female brain volume), or ascending neurons for which the axonal arbors in the brain are too small to identify them in FAFB/FlyWire (Extended Data Fig 3f). Proportionally, a modest 0.1% of neurons in the male visual system are sex-specific and 0.3% are sexually dimorphic, compared to less than 0.1% sex-specific and 0.4% sexually dimorphic neurons in the female (Extended Data Fig 3f). In the central brain, dimorphism is much more prevalent: 3.4% of neurons are male-specific and 1.2% (1% in the female) are sexually dimorphic (Fig 3h). By contrast, female-specific neurons make up only 1% of the central brain.

Where do these sex-specific neurons originate? Female-specific neuronal apoptosis during pupal development leads to an abundance of male-specific neurons that survive through adulthood[61]. Of the ~200 hemilineages forming the central brain[62,63], about a quarter produce sex-specific or sexually dimorphic neurons; 8 of these (4%) produce more than 50% of all

sex-specific and dimorphic neurons (Fig 3j; Extended Data Fig 3g). Hemilineages containing male-specific cell types, such as DM4 dorsal, tend to have more neurons in males than females (349 vs 205). Excluding sex-specific neurons helps symmetrise the number of neurons per hemilineage across sexes (DM4 dorsal: 199 male, 201 female). Approximately 35% of sexually dimorphic and sex-specific neurons are primary (embryonic born), or for other reasons could not be assigned a hemilineage.

Topology of sexual dimorphism

Sexually dimorphic neurons are characterized by distinct morphological and connectivity features. These dimorphisms present in various ways, including as extra axonal and/or dendritic arbours or shifted neurites. Extra arbours on sexually dimorphic neurons can be entirely *de novo*, expand or shift existing branching patterns, or in some cases comprise a complex combination of these features (Fig 3d). A clear example of *de novo* arborisation is the dimorphic cell type AOTU008 (part of aSP-i in Cachero *et al.,* 2010) which extends medio-ventral axonal projections in males that are absent in the female homologues (Fig 3e)[27]. These neurons are enriched in dimorphic and sex-specific connection partners (5.5% of inputs and 57% of outputs). Surprisingly, the abundant dimorphic connections are not exclusively localized to the male-specific arbours, which make connections onto isomorphic as well as dimorphic/sex-specific downstream partners (Fig 3f). For example, AOTU008 makes all of its connections to the isomorphic descending neuron DNp05 from its male-specific branches, while synapses to the male-specific VES202m are distributed across the entire axon (Fig 3g). This synaptic organization suggests that, while extra branches on dimorphic neurons tend to be involved in connections with dimorphic/sex-specific partners, they are not necessarily always the principal site of connectivity. Sex-specific branches may be required to form *de novo* connections to isomorphic circuit elements that would otherwise not be within reach: AOTU008 cannot connect to DNp05 in female brains simply because their neurites are too far apart. Conversely, if the synaptic partner, like VES202m, is dimorphic or sex-specific itself, connections may involve the entire neuron. We will further explore this anecdotal observation in later sections.

To assess where dimorphism is located in the brain, we quantified the synaptic distribution of sex-specific and dimorphic neurons. Most of the dimorphism is localized in higher-order brain regions, principally the protocerebrum. Surprisingly, we also find enrichment in the lobula (LO) and gnathal ganglion (GNG), more basal neuropils. These neuropils showed consistent enrichment whether we assessed pre- or postsynaptic sites (Fig 3k, Extended Data Fig 3h,i). Except for the superior clamp (SCL), the same neuropils are enriched for sex-specific or sexually dimorphic neurons in both sexes, although the relative degree of enrichment varies. The primary difference across sexes are in the SMP and SIP, which are enriched in the male and female, respectively. These results largely align with the findings from Cachero *et al*.[60], in which the male and female-specific projections of *fruitless*-expressing neurons were shown to be highly enriched in the protocerebrum.

Next, we characterized the topological distribution of sex-specific, dimorphic, and isomorphic neurons within the connectome graph using a probabilistic graph traversal model[64] (Fig 3l). This method assigns “layers” to individual neurons which represent an intuitive ordering relative to some seeds: in this case, sensory inputs. Isomorphic neurons are distributed relatively evenly across 7 layers with a mean at layer 3.9. In contrast, sex-specific and

dimorphic neurons tend to occupy deeper layers, with a mean at layer 4.3 and 4.5, respectively. The early olfactory system, for example, broadly covers layers 1 (olfactory receptor neurons, ORNs) to 3 (antennal lobe projection neurons, ALPNs). Only 2.5% of male-specific and 5.5% of dimorphic neurons appear in that range, compared to 18.5% of isomorphic neurons. This supports the hypothesis that sexual dimorphism is a feature of higher (deeper) brain circuits while early sensory processing is largely isomorphic. We explore this observation further in the following results sections.

Genetic basis for dimorphism

Sex differentiation in *Drosophila* is ultimately controlled by the alternative splicing of two master regulator genes, *fruitless* (*fru*) and *doublesex* (*dsx*), which shape the developmental trajectories of neurons to give rise to sex differences in morphology and synaptic connection partners[19,65,66]. Using whole-brain connectomes, we can, for the first time, comprehensively assess the correlation between the expression patterns of these genes and resulting sex-differences.

We manually compared neurons in the male CNS and FAFB/FlyWire connectomes with light microscopy datasets and annotated them as putatively expressing *fruitless*[60,67] and/or *doublesex*[27] (Fig 3m; see Methods). This analysis was principally focused on the central brain, but we did annotate a small number of *fruitless* and *doublesex*-expressing neurons in the VNC based primarily on previous annotations from the MANC dataset[55,68].

To account for uncertainty, we categorised *fru*- and *dsx*-expression as either high- or low-confidence: high confidence was assigned to cell types that matched the canonical shape or were fully contained inside of the light-level data, and to cell types that were shown to express *fru/dsx* based on immunohistochemistry or transcriptomic data[68,69]. This enabled us to provide lower and upper bounds with respect to *fru*/*dsx* expression estimates.

We identified 4,505 (2,695 high confidence) putatively *fruitless*- and 407 (332 high confidence) putatively *doublesex*-expressing neurons in the male CNS, accounting for 2.7% and 0.2% of the volume, respectively (Extended Data Fig 3j). Of these, we identified 251 cells as co-expressing both transcription factors. The majority (73%) of *fruitless*/*doublesex* annotations are in the central brain, 8.1% are in the VNC, and 9.5% are in the optic lobes (Extended Data Fig 3l). We estimate *fruitless* expression in approximately 9.5% of central brain neurons in the male – 4.7% if counting only high-confidence annotations. Because most of the light-level data labels large populations of neurons which makes identifying individual neurons difficult, our counts likely represent an upper boundary.

To validate the *fru/dsx* annotations, we compared our observed values to those expected from previous studies[27,60,61]. Considering only the brain lineages observed in Cachero *et al.*[60], we identify 2,905 *fru*+ neurons in males and 2,068 *fru*+ neurons in females, compared to the expected 1,993.6(±75.7) and 1,668.4(±60.6), respectively. For *dsx*+ lineages reported in Nojima *et al.*[27], we find 342 *dsx*+ cells in males and 134 in females, compared to 387.4(±18.6) and 66(±4.4) expected neurons (Extended Data Fig 3j). For FAFB/FlyWire, our estimates are broadly consistent with a recent study in the same dataset[70] (see Methods for details). Breaking this down per lineage shows that much of the discrepancy stems from lineages where prolific cell types have common morphologies, and this is consistent across sexes (Extended Data Fig 3g). It is difficult to discern whether our labels are too inclusive, or

whether methodological limitations in prior studies resulted in an underestimate. If the former is true, cell types with similar morphology may not always collectively express *fru* or *dsx*.

Past studies relied on *fru*/*dsx* expression as the best proxy for sexual dimorphism. Comparative connectomics now allows us a comprehensive and orthogonal evaluation of sexual dimorphism. How does the expression of *fruitless* and *doublesex* correlate with neurons identified as dimorphic? 89.1% of male-specific neurons in the central brain were annotated as putatively expressing one or both of *fruitless* and *doublesex*, compared to 60.8% of sexually dimorphic neurons and only 6.4% of isomorphic neurons. The fraction of neurons identified as putatively expressing *fruitless* and/or *doublesex* is similar across sexes (Fig 3n). Conversely, 11% of sex-specific and 39.2% of sexually dimorphic neurons do not seem to express either *fruitless* or *doublesex*. Some of this discrepancy likely results from incomplete expression data for *fruitless* or *doublesex* (see Methods); however, the possibility remains that, in some cases, other genetic factors or non-cell autonomous mechanisms could be responsible for shaping these dimorphisms.

The rich literature describing dimorphism in *Drosophila* has, among other things, examined dimorphic cell types, connectivity, genes, circuits, and behaviours[10,19,20,22,24,26,27]. We provide `synonyms` that facilitate cross-referencing of cell types to specific publications or resources, such as “aSP-g” as published in Kohl *et al.*[26]. In total, we recorded 200 distinct synonyms for over 800 cell types: 75% of male-specific, 70% of female-specific, and 34% (51% in female) of sexually dimorphic neurons have a synonym (Fig 3o). We were unable to match 82 male-specific, 33 female-specific, and 73 dimorphic cell types to the literature, suggesting that 37% of dimorphic/sex-specific cell types described in this study may be novel.

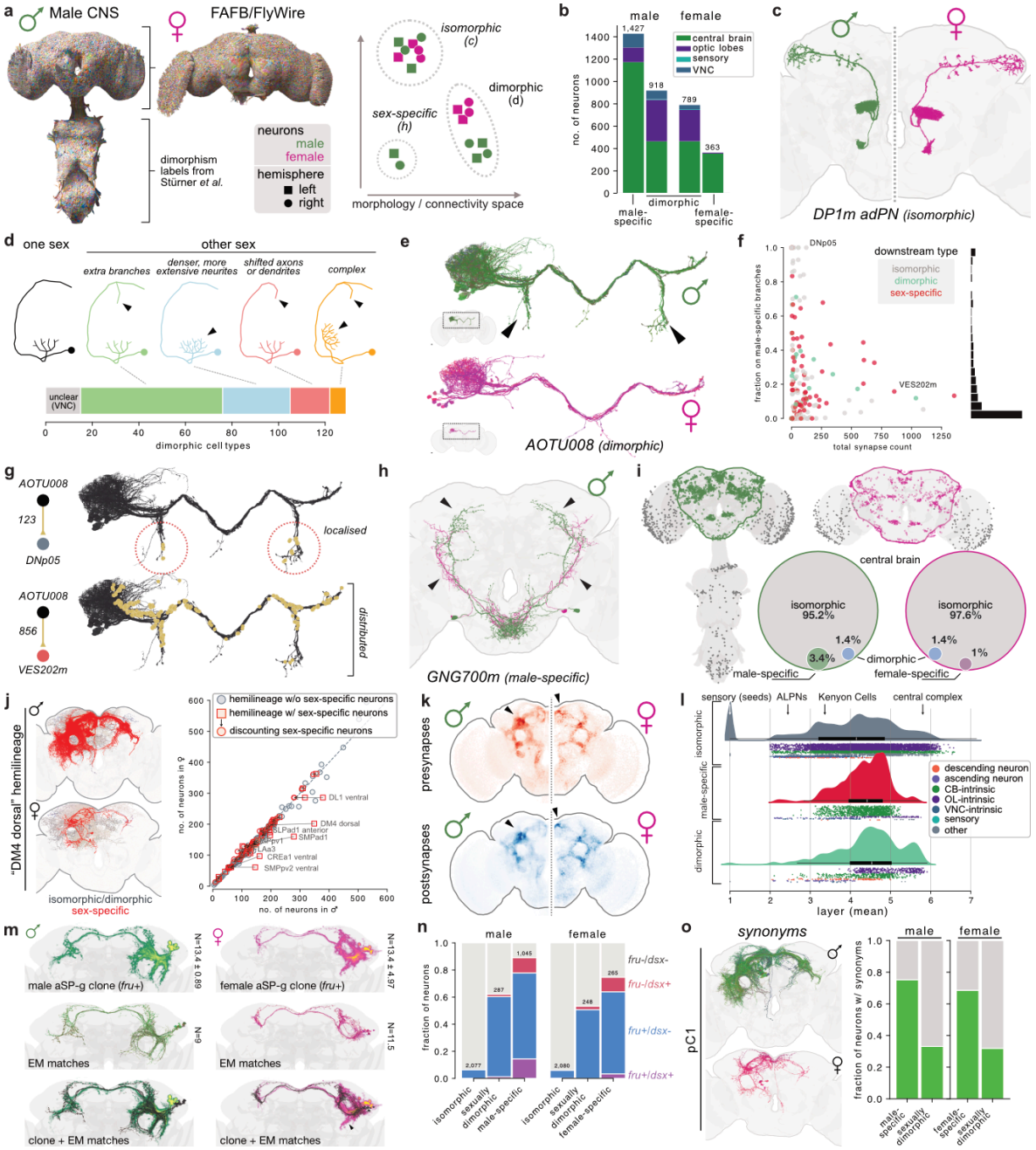

Figure 3 | Sexual dimorphism in the fly brain.

a Schematic illustrating differences between iso- dimorphic and sex-specific neurons in morphology or connectivity space. See also Table 1. **b** Number of dimorphic & sex-specific neurons broken down by superclass. **c** Example for isomorphic cell type. **d** Classification of dimorphic types based on morphological differences in the brain. **e** Example for dimorphic cell type with extra branches. Arrowheads highlight ventro-lateral axons only present in male neurons of this type. **f** Fraction of synapses on male-specific branches vs total synapse count for each outgoing connection made by AOTU008. **g** Examples for distributed connections and connections highly localised to male-specific branches. **h** Example for sex-specific cell type: GNG700m (green). The closest isomorphic cell type (AVLP613, magenta) is shown for comparison. Arrowheads point out differences in axonal projections. **i** Spatial distribution of dimorphic and sex-specific neurons' somata. Central brain somas are coloured in green and magenta for male and female, respectively. Pie charts show the proportion of central brain neurons that are dimorphic/sex-specific. **j** Left: example hemilineage in male and female with sex-specific neurons highlighted in red. Right: neuron count per hemilineage in male vs female. Discounting sex-specific neurons tends to align

numbers. The labelled hemilineages collectively produce >50% of all dimorphic & sex-specific neurons in the male. **k** Distribution of pre- (outputs) and postsynapses (inputs) of dimorphic & sex-specific neurons in male and female connectome. Arrowheads highlight differences between sexes. **l** Layer assignments relative to sensory inputs for all neurons in the male CNS split by dimorphism. Data points are coloured by superclass. Top half shows the kernel density estimate of the underlying distribution. Mean layers for antennal lobe projection neurons (ALPNs), Kenyon Cells and central complex neurons are shown as landmarks. **m** Light-microscopy (LM) image of a *fruitless* (*fru*+) clone (top row) and matching neurons found in the EM (middle row)[60]. Arrowhead points at variable branches in female aSP-g clones. **n** Fraction of neurons in the central brain labeled as *fruitless*- and *doublesex*-expressing (*dsx*+) based on LM-EM matches. **o** Left: pC1 (includes P1 neurons) as an example for a synonym assigned to a group of dimorphic neurons. Right: fraction of dimorphic neurons matched to prior literature.

Visual system

Drosophila use their visual system to detect environmental light cues for behaviors like navigation and circadian regulation, as well as specific object features such as shape, movement and colour. In *Drosophila*, the visual system is housed primarily in the optic lobes. These consist of five main neuropils (the lamina, medulla, lobula, lobula plate, and accessory medulla) and contain four principal cell superclasses (sensory, optic lobe intrinsic, visual projection, and visual centrifugal neurons) (Fig 4a). A full catalogue of the right optic lobe neurons in this male CNS connectome was presented in Nern *et al.*[36]. Here we expand our analyses to the left optic lobe. We observe excellent agreement between cell types, cell counts and connectivity between the two optic lobes (Extended Data Fig 4Ba-e). We also improve our annotations of pale and yellow column types in the medulla of both optic lobes (Extended Data Fig 4Bf-j and see Methods); see also the updated Cell Type Explorer web companion for comprehensive optic-lobe-specific analyses.

The inclusion of the left optic lobe enables the bilateral visual networks of the male to be compared to those in the female. Male fruit flies rely heavily on visual information to direct courtship displays: chasing, ipsilateral wing preference, and overall courtship success are associated with the effective transmission of visual signals[22,71–73]. To investigate potential sexual dimorphism in the visual system, we quantitatively compared the anatomy of cells across male[36] and female[74] optic lobes. We found high concordance between male and female, with 98.8% of optic lobe neurons matched to FlyWire (Fig 4b)[36,75] and comparable neuron counts per type (Fig 4c).

Of 249 cell types intrinsic to the optic lobe, we have thus far identified 3 (Cm26, Tm26 and Mi20) which are sex-specific (Fig 4b,d), and 1 (TmY21) that is sexually dimorphic (Fig 4b,l). Strikingly, 99.9% of all visual projection neurons (VPN) are sexually isomorphic, and we identified just a single male-specific cell type: LoVP92 (Fig 4b,d). Three cell types remained unmatched due to bilateral inconsistency (Fig 4b, Extended Data Fig 4Aa). We did not find sex-specific or sexually dimorphic sensory or visual centrifugal neurons (Fig 4b).

LoVP92 consists of 13 cells, around 6 per side, with dendrites spanning the dorso-ventral axis of the anterior lobula, receiving 14.7% of their inputs from sexually dimorphic TmY21 neurons and 2.8% from male-specific Tm26 neurons (Extended Data Fig 4Ad). These neurons commit 42.6% of their output to sex-specific and sexually dimorphic downstream targets (Fig 4i). Furthermore, their distinctive axonal arbours define a node of sexual dimorphism where multiple male-specific and sexually dimorphic types converge. For

example, multiple male-specific central brain interneurons (PVLP214m, PVLP207m, VES200 and VES202m) send axons that converge on this node (Fig 4e, Extended Data Fig 4Ab). These local interneurons are strong downstream partners of multiple sexually isomorphic VPN types (such as LLPC4, LT78, LT86, LT84, Fig 4n). This architecture effectively converts these isomorphic VPNs into functionally dimorphic types by wiring their axons into the same location as LoVP92 axonal arbours. Similarly, several dimorphic descending types (including DNpe002, DNg111, DNg13 and DNge103) have large isomorphic dendrites innervating distinct territories, and a small dimorphic dendritic arbour that is confined to the same region as the LoVP92 axons (Fig 4f, Extended Data Fig 4Ac). These dimorphic branches are themselves heavily enriched in dimorphic and sex-specific partners compared with the isomorphic portion of the neuron (Fig 4f, Extended Data Fig 4Ac). In summary, the node defined by the axons of LoVP92, the only male-specific VPN, may serve as a male hotspot, where multiple dimorphic cell types converge to participate in male-specific circuits (Fig 4g, left). We anticipate the presence of numerous additional hotspots within other central brain regions characterised by a high density and diversity of dimorphic connections (Fig 4g, right).

While the gross anatomy of the visual system itself is largely isomorphic, visual information directly flows via VPNs to sex-specific and sexually dimorphic circuits in the central brain. Nineteen out of 337 VPN types direct over 9% of their output to sexually dimorphic or sex-specific downstream neurons in the male (Fig 4i). For example, the isomorphic LC10a neurons, critical for accurate tracking during courtship[32,73,76,77], target sexually dimorphic AOTU008 neurons in both sexes[27], but AOTU008 sends ventral axonal projections to the EPA in males only (Fig 3e-g) and commits 57% of its output to sex-specific and/or dimorphic downstream partners.

We next investigated the visual space sampled by the VPNs enriched in sex-specific and sexually dimorphic synaptic partners and found that 7 of the 19 types (highlighted in grey in Fig 4i) feature inputs synapses biased towards the frontal visual field (Fig 4j, Extended Data Fig 4Ae,g)[78]. While many VPN types cover the entire lobula, the dendrites of several – LT84, LLPC4, LoVP92, LC43, LT78, AOTU045, and LT86 – are confined to the anterior part of the lobula, corresponding to ommatidia in the fronto-medial part of the compound eye which sample the frontal visual field. A subgroup of anterior LC10a VPNs upstream of AOTU019 was previously reported to be involved in precise steering toward the midline[77]. As expected, this subgroup also shows a bias towards the fronto-medial visual space. Strikingly, the bias is even stronger for some of the other VPNs. With the exception of LC43 and LT86, these frontally-biased VPNs receive a high proportion of input from the sexually dimorphic interneuron TmY21 (Fig 4k). Inputs to TmY21 in the medulla also show a spatial bias. This is apparent both in the distribution of their total medulla inputs (Extended Data Fig 4Af) as well as the inputs, in particular Dm3a-c neurons, to prominent male-specific branches in layer M3 (Fig 4l,h). The connection weights of the Dm3 to TmY21 connections were much stronger in males than in females (Fig 4m).

Taken together, this circuit organisation suggests a model in which frontally biased VPNs that connect onto strongly dimorphic circuits in the central brain reroute the flow of visual information to support sex-specific social behaviours. The receptive field bias is consistent with behaviours such as courtship, during which males pursue females from behind by maintaining them within the frontal field of view[29,73,79,80]. This specialised

processing of a distinct region of visual space is also reminiscent of at least two long-appreciated features of visual organisation, the fovea and the insect "love spot". Larger flies have a love spot[81], where male eyes feature specialised photoreceptors[82] that are proposed to be tuned for visual target tracking during courtship[83–85]. While *Drosophila* males lack the prominent external eye specialisations present in larger flies, the frontally-biased VPNs may serve an analogous function to male-specific/dimorphic neurons in other insects that sample the visual space imaged by the love spot[86,87]. Secondly, recent observations in both sexes show that the *Drosophila* visual system has features of the foveal specialisations found across species, including mammals: higher acuity eye regions[78] and their over-representation in optic lobe circuits[36]. The link with these two themes is further strengthened by the fact that these high acuity regions exhibit sex-specific connectivity, specifically the Dm3-TmY21 connections upstream of the frontally-biased VPNs (Fig 4h–m; Extended Data Fig 4Af).

In order to link these neurons to sexually dimorphic behaviour, we investigated descending visual pathways downstream of the frontally-biased VPNs and identified 11 descending neurons, including DNa02 and aSP22, which have previously been shown to be involved in navigation during courtship pursuit[77] and subsequent aspects of the courtship sequence[88] (Fig 4n, Extended Data Fig 4Ah,i). Beyond these pathways with characterized roles in courtship, we found additional connections supporting central object tracking and navigation during pursuit. For example, LoVP92 is connected to the descending steering neuron DNg13[89] via the male-specific interneuron VES200m which is predicted to be GABAergic (Fig 4o)[90]. The DNg13 pathway is thought to contribute to coarse steering. When the female is positioned frontally, activation of LoVP92 inhibits this pathway, thereby allowing other descending pathways downstream of frontally biased VPNs to dominate, potentially enabling finer tracking near the midline.

Our findings provide circuit-level evidence for a behaviourally relevant “love spot” in *Drosophila melanogaster*: male flies detect fly-sized objects in their central visual field [73], and this information traverses sexually dimorphic neural circuits through to descending pathways likely facilitating successful courtship pursuit.

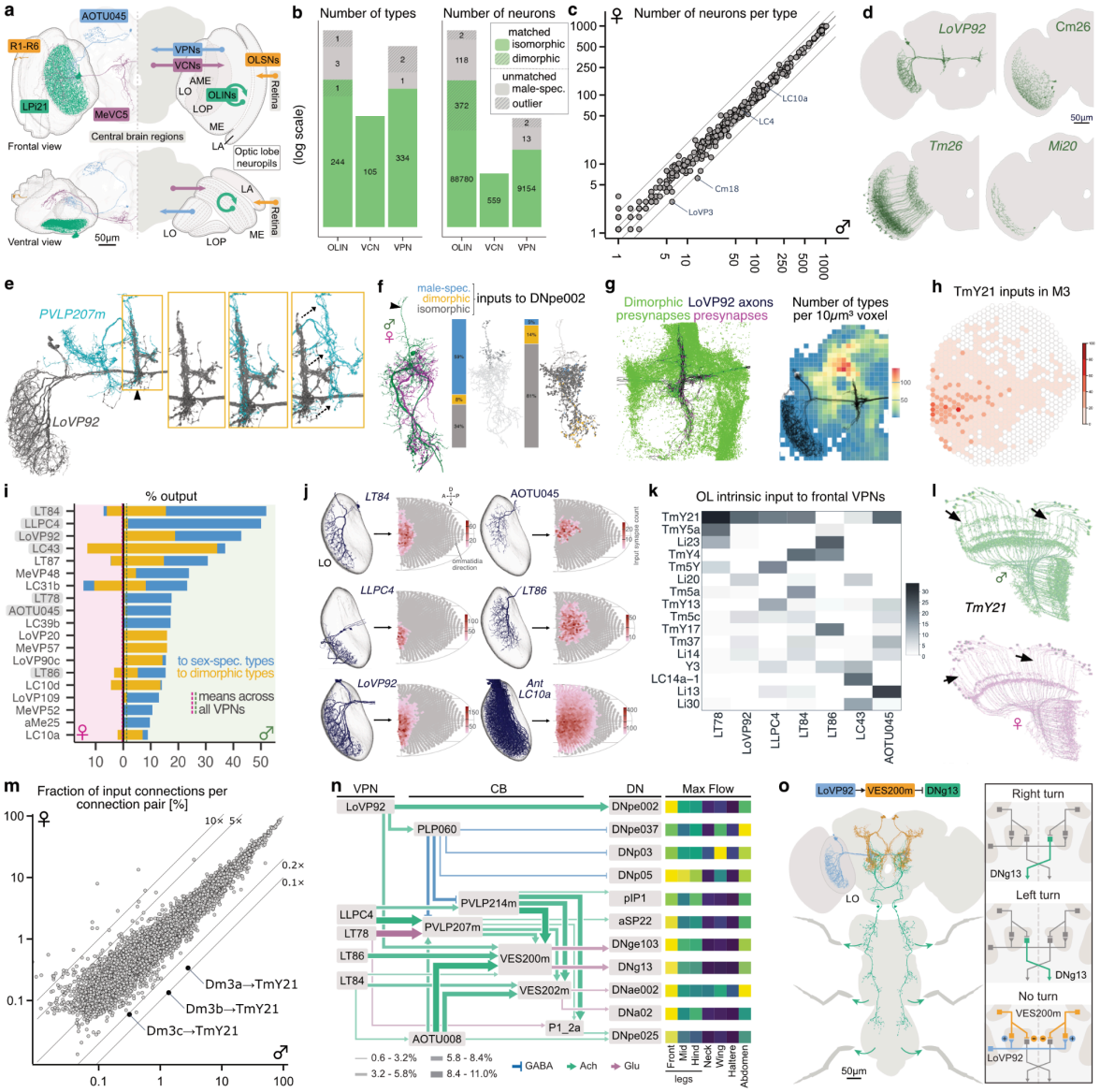

Figure 4 | Sexual dimorphism in the visual system reveals a functional "love-spot"

a Diagram of the optic lobe, showing the different neuropils and neuronal superclasses. LA: lamina; ME: medulla; LO: lobula; LP: lobula plate; AME: accessory medulla; OLSNs: optic lobe sensory neurons; OLINs: optic lobe intrinsic neurons; VPNs: visual projection neurons; VCNs: visual centrifugal neurons. **b** Number of types (left) and neurons (right) per superclass across several categories. A type was classified as male-specific only if it was symmetrical; otherwise, it was annotated as unmatched outlier. **c** Neuron count per type between male and female. Female counts were normalised (x1.134) to account for the ~100 additional ommatidia in the male eye. Only types matched one-to-one between males and females are included. Photoreceptors and Lai are excluded, as many are missing in the male CNS. **d** The four male-specific visual types. Scale bar, 100 µm. **e-f** Examples male-specific (e) and dimorphic (f) types that converge onto LoVP92 axons. Inset: close-up and shifted view of the boxed area in e. Arrowheads indicate the location of LoVP92 axons. Stacked bar charts show the input-normalized proportion of dimorphism status of connection partners onto DNpe002. **g** Dimorphic synapse distribution around LoVP92 axons (black). Green dots show all synapses between dimorphic or sex-specific types. LoVP92 output synapses are shown in magenta. Right: heatmap showing the number of cell types per 10 µm³ voxel in the right hemisphere of the central brain. **h** Spatial map showing Dm3a,b,c inputs to TmY21 in the third layer of the ME. **i** Output-normalized percentage of VPN outputs to dimorphic or sex-specific types in the female (left) and the male (right). Dotted lines indicate the average

percentage output from all VPNs onto sex-specific or dimorphic partners. **j** Examples of frontally-biased VPNs. Spatial coverage heatmaps show input synapse distributions mapped onto a Mollweide projection of the right compound eye's visual field. Color scale bars show input synapse count. **k** Heatmap showing the strongest inputs from optic lobe intrinsic neurons to frontally-biased VPNs. **l** The dimorphic type TmY21 in the male (top) and female (bottom). Arrowheads indicate differences in arborisation between the sexes. **m** Fraction of input connections for each pair of connections between optic lobe intrinsic neurons in the male and female. Only edges with more than 500 synapses are shown. Lines indicate changes in relative weight by factors of 5 and 10. **n** Network diagram showing male-specific connections between frontal VPNs and DNs. Only DNs reached within two hops were included, using a 2% input threshold – except for DNa02 and DNae002, where a 0.5% threshold was used. AOTU008 did not meet the DN threshold but was included because its top two input partners are VES200m and VES202m. **o** Diagram of a frontal VPN to DN circuit in the fly brain and nerve cord (left), alongside a simplified circuit diagram (right). VES200m links visual detection – via LoVP92 inputs from the lobula – to the steering descending neurons DNg13. Unilateral activation or inhibition of DNg13 has been shown to cause ipsilateral, or contralateral, turning, respectively. LoVP92 activates VES200m bilaterally, and VES200m inhibits DNg13 ipsilaterally. As a result, activation of LoVP92 leads to inhibition of both DNg13 neurons, preventing turning.

Auditory system

Auditory cues are central to *Drosophila* courtship behaviour. Male flies vibrate their wings to produce species-specific songs, enabling females to assess species identity and mate quality[91–94]. *D. melanogaster* males generate two main song types, pulse and sine song, controlled through nested networks in the wing neuropil of the nerve cord[55,95]. These songs elicit sexually dimorphic responses: receptive females reduce their locomotion and open the vaginal plate for copulation[58,93,94,96–98], while males become aroused, leading to increased locomotion, persistent courtship displays, and intermale competition[99–103].

Several song-responsive neurons have been identified in male and female *Drosophila*[99,101,102,104–107]. Courtship song detection begins in the antennal Johnston's organ (JO), where mechanosensory neurons are arranged in discrete frequency-tuned channels that project a tonotopic map in the brain[108,109]. The sensory subtypes that are physiologically tuned to the low frequency of courtship song are called JO-B because they innervate zone B of the antennal mechanosensory and motor centre (AMMC)[101,110]. Despite segmentation issues with sensory neurons in the antennal nerves, we were able to identify around 20% of JO-B neurons (Extended Data Fig 5a). Consistent with previous literature, we found no evidence that these sensory neurons are themselves sexually dimorphic[99,101,102,104,111].

In both sexes, JO-B neurons relay auditory information to aPN1, a *fruitless*-expressing but isomorphic population innervating the wedge neuropil (WED) and zone B of the AMMC[99,101] (Fig 5a). These neurons comprise part of the AMMC-B1 population[105], and are essential for detecting courtship song, preferentially responding to pulse song[101,105,111]. Additional auditory neurons, including aLN(al), aLN(m), and wedge/ventrolateral protocerebrum (WED/VLP) (WV-WV) cell types from Vaughan *et al*.[101] and Baker *et al*.[105] are annotated as synonyms for 8 other cell types, according to comparison with light-level data.

Female sexual receptivity depends on vaginal plate opening descending neurons, vpoDNs, which are modulated by excitatory (vpoEN) and inhibitory (vpoIN) populations tuned to

conspecific courtship song[51]. We identified vpoEN and vpoIN in the male CNS dataset and, perhaps unexpectedly, found no clear morphological dimorphism compared to FAFB/FlyWire (Fig 5c, Extended Data Fig 5c). While these neurons do not appear to be dimorphic themselves, approximately half of vpoEN outputs (but not inputs) are onto sexually dimorphic or sex-specific cell types in males and females. For vpoIN, outputs are more variable: 3 out of 5 male vpoIN neurons connect predominantly to dimorphic or sex-specific downstream cell types. In contrast, all female vpoIN neurons primarily target isomorphic types (Fig 5d). To compare circuit components across sexes, we took the top input and output partners of vpoEN and vpoIN and found partners shared between sexes and partners unique to one sex. For example, DNp55 is downstream of both male and female vpoEN, while vpoDN and P1_6a are downstream partners specific to female and male vpoEN, respectively (Fig 5b,c). This circuit architecture exemplifies a changeover switch: male and female brains reroute the same sensory information by wiring the same circuit component (vpoEN) to sex-specific downstream neurons (vpoDN and P1_6a).

In males, courtship song induces chaining behaviour through aPN1 and male-specific vPN1 neurons[99]. vPN1 is a *fruitless*-expressing cell type that projects to the ventrolateral protocerebrum, a brain area rich in dimorphic synapses (Fig 3k, Extended Data Fig 3h,i). These cells respond to pulse and sine song, and were shown to be functionally related to male-specific P1 neurons[99]. Despite previous indications of direct excitation of P1 by vPN1[99], our neurotransmitter predictions suggest that the entire LHl1 hemilineage, including vPN1, is GABAergic. The likely mechanism for P1 activation is therefore through disinhibition via intervening GABAergic interneurons (Extended Data Fig 5e). Connectomic analysis suggests a circuit involving a male-specifc mAL subtype as a candidate for maintaining excitation-inhibition (E/I) balance onto P1, possibly switching male behaviour between aggression and courtship.

Downstream circuits of vpoEN, vpoIN, and vPN1 include many *fruitless*-expressing nodes, as well as song-generative DNs like pIP10[23] and pMP2[55]. Extensive work characterising the neural circuit architecture underlying song production has identified key nodes in the wing neuropil of the ventral nerve cord, including TN1A, vPR9, and dPR1 [55]. Here, we identify these circuit elements in the male CNS dataset, and identify a set of male-specific ascending neurons, AN08B074 and AN08B084, that feed information from the song generation motor circuits in the VNC back to the song detection circuit in the central brain. These results support previous work suggesting that AN-mediated feedback contributes to circuit-level coordination[49,56]. AN08B074/084 both receive information from and project information to song detection pathway neurons, including the *fruitless*-expressing aSP-a and pIP-e populations, as well as DNs including pMP2, pIP10, and DNp36 (Fig 5b,e, Extended Data Fig 5g). This bidirectional connectivity creates a closed loop in which the motor output of singing directly influences sensory detection, thereby modulating song perception according to a fly's current motor behaviour. This feedback loop may function as an efference copy – a neural mechanism that provides real-time information about self-generated motor actions – allowing males to distinguish their own song from that of others[112]. We propose this recurrent feedback loop modulates male arousal state by integrating information about ongoing motor output with incoming sensory signals to flexibly control wing extension according to the auditory environment.

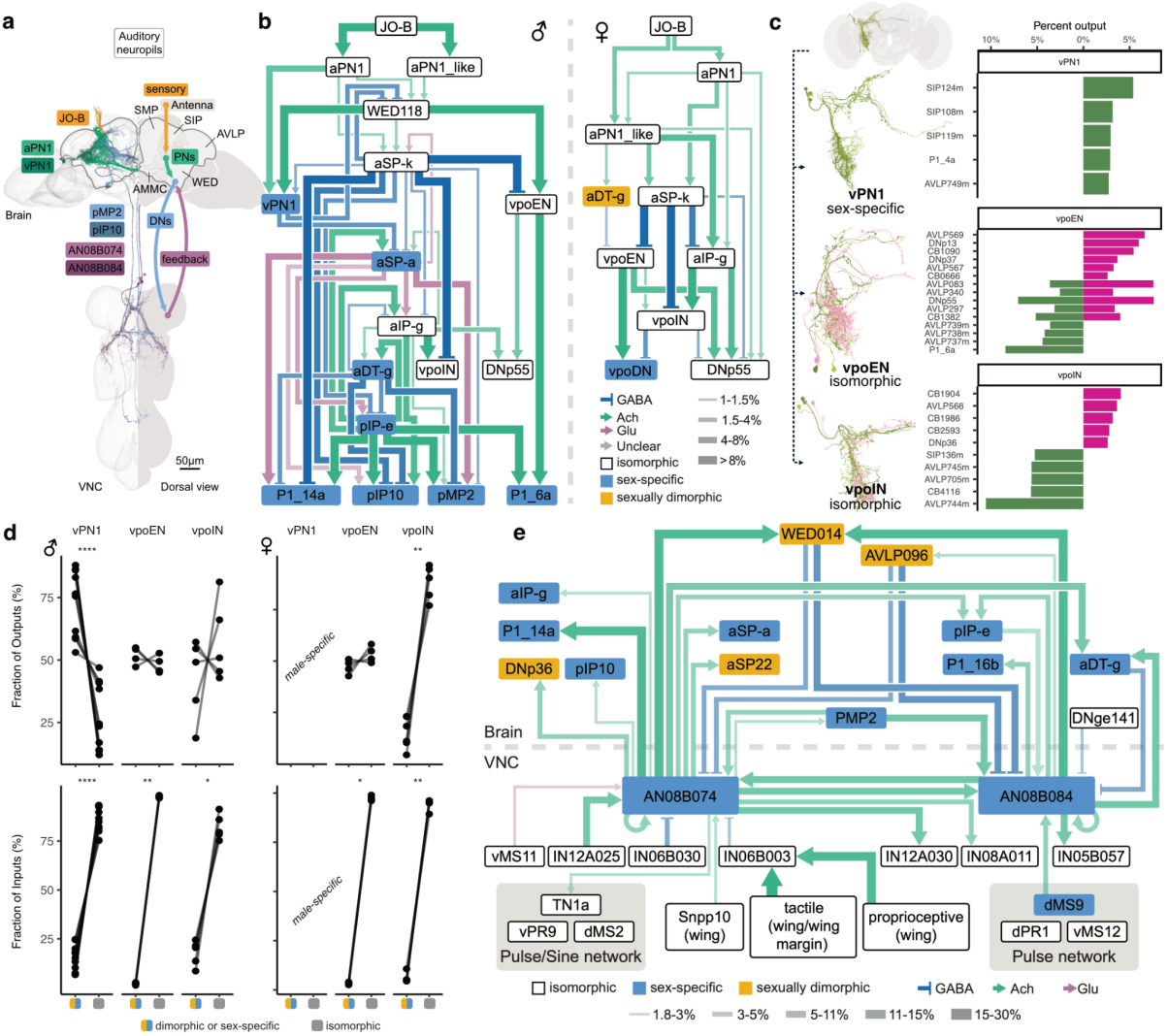

Figure 5 | A recurrent feedback loop controls courtship song detection and action in the auditory system

a Overview of the auditory pathway and recurrent feedback circuit. Song induced vibrations move the arista to activate Johnston's organ B neurons, activating a sensorimotor loop that provides feedback from song generating networks back to the central brain. **b** Circuit schematics for male (left) and female (right) from JO-B to higher order processing centres. Boxes denote cell types, edge thickness scales with synaptic weight, and edge colors indicate transmitter identity. Node colors mark sex classes: isomorphic (white), sexually dimorphic (gold), sex specific (blue). Line widths denote input-normalized connection strengths. **c** Top output partners (>2.5%) of vPN1 (top), vpoEN (middle) and vpoIN (bottom) in males and females. Bars show the fraction of total synaptic outputs (right) (output-normalized) sent to each identified type across sexes. **d** Quantification of partner identity for vPN1, vpoEN, and vpoIN. Top: fraction of outputs targeting dimorphic or sex specific versus isomorphic neurons. Bottom: fraction of inputs from dimorphic or sex specific versus isomorphic neurons. Each dot is one neuron and paired points are linked. Means were compared using Wilcoxon two-sample tests: ns: $p>0.05$; ****$p\leq0.0001$; ***$p\leq0.001$; **$p\leq0.01$; *$p\leq0.05$. **e** Connectivity between central brain song detection and ventral nerve cord song production circuits. The established pulse and sine song network in the wing neuropil is reproduced and connected to identified descending neurons and to male specific ascending neurons that project back to central brain nodes. Line widths denote input-normalized connection strengths. Scale bars as indicated.

Olfactory system

Olfactory cues are key drivers of sexually dimorphic behaviour in many species[113]. In flies, volatile pheromones, some of which are sex-specific, elicit different behavioural responses in males and females[114]. Changes in the morphology and connectivity of pheromone-responsive neurons have been found in higher brain areas such as the lateral horn[26,115] but not in the early olfactory system[114,116]. Using the connectome, we can follow pheromone signals all the way to the first order olfactory centre (the antennal lobe, AL), analogous to the mammalian olfactory bulb, Fig 6a) and examine in detail where there may be sex differences in processing.

The *Drosophila* olfactory system consists of approximately 1,300 olfactory receptor neurons (ORNs) in each hemisphere grouped into 53 types according to their receptor expression profiles[117–120]. ORNs expressing the same receptors project to the same antennal lobe compartment, or glomerulus, where they synapse with second-order projection neurons (ALPNs) that carry sensory information from particular glomeruli to higher brain centres. Antennal lobe local neurons (ALLNs) provide lateral inhibition and excitation[121]. In parallel, the AL also integrates thermo- (heat) and hygro- (humidity) sensation in distinct glomerular subcompartments in the AL (VP glomeruli, VP1-5) through their own receptor neurons (TRNs and HRNs, respectively). There are around 100 of these neurons grouped into 7-8 types[48]. We use “RNs” to collectively refer to olfactory, thermosensory, and hygrosensory receptor neurons, and “ORNs” when referring exclusively to olfactory neurons.

Four pheromone-responsive glomeruli have been identified: DA1, DL3, VA1d, and VA1v, innervated by ORNs expressing OR67d, OR65a, OR88a, and OR47b receptors, respectively[114,122,123] (Fig 6b). DA1 and DL3 ORNs are finely tuned to 11-cis-vaccenyl acetate (cVA), a male-secreted sex pheromone that acts as a female aphrodisiac and promotes aggression in males[114,124]. VA1v and VA1d ORNs preferentially respond to fly-derived odorants present in both sexes, including methyl laurate, which promotes male copulation and female aggressive behaviours[122,125,126]. A fifth glomerulus, VL2a, has also been shown to promote courtship although its receptor, Ir84a, is tuned to fruit-derived odours rather than pheromones[127].

We identified RNs for all 53 olfactory and 7 thermo/hygro-glomeruli and cross-matched them between male CNS, FAFB/FlyWire and hemibrain. While the majority of RNs (~70%) were fully reconstructed, these fine sensory neurons were amongst the most challenging in the dataset due to image/segmentation issues (see methods and Extended Data Fig 6a,b for details). Nevertheless we were able to begin our investigation of sex differences in the peripheral olfactory system, by comparing RN numbers between the male CNS and FAFB/FlyWire (Fig 6c). Sorting glomeruli by the difference in the number of sensory neurons observed between males and females, highlighted the DA1, VA1v, VA1d and VL2a glomeruli as having a male bias. This is notable given their relationship to pheromone detection/social behaviour as noted above and that it includes all three ORN types that express the *fruitless* gene (DA1 and VA1v, and VL2a ORNs). For the remaining ORN types, there was good agreement between the numbers in female and male connectomes.

Classic studies in moths have linked male-enlarged glomeruli to processing of specific pheromone blend components detected by receptor neurons that are numerically enriched

on the male antenna[128]. Prior studies in *Drosophila* based on light microscopy have noted volumetric dimorphism in three of the four glomeruli highlighted in our analysis[129] but have not identified any sex differences in numbers of receptor neurons[130]. While our examination of n=2 sample brains precludes formal statistical analysis, the targeted numerical differences that we observe in four biologically relevant glomeruli strongly suggest that this is a true sex difference. Comparative studies across drosophilid species show that an increase in the number of ORNs leads to reduced adaptation in the responses of downstream ALPNs to long-lasting or repetitive stimuli, in part due to decreased lateral inhibition[131]. Pheromone-responsive ORNs may therefore employ a similar mechanism to enable tracking of odours during the tens of minutes typical of courtship.

Given these differences in ORN counts for some glomeruli we looked to see if there were any changes in connectivity with their downstream uniglomerular ALPNs. We did observe a trend towards higher ORN and lower ALLN input onto ALPNs in males than in females; however, this was a general trend for all neurons in these classes (Fig 6d). Furthermore, when we compared connectivity of these three main AL cell classes (ORNs, ALPNs and ALLNs) for the male CNS and two female datasets (FAFB/FlyWire and hemibrain) (Extended Data Fig 6c) we found that FAFB/FlyWire is the outlier. This strongly suggests that differences observed initially are technical in origin since the hemibrain and male CNS were imaged using different electron microscopy technology. This example highlights the need for careful analysis of connectivity differences, particularly when interpreting global trends for a class of neurons as opposed to changes between specific cell types of the same general class.

After this initial investigation, we broadened our analysis to include all output neurons of the antennal lobe. While many of these neurons have dendrites innervating a single olfactory glomerulus, others, which have historically received less attention despite the fact that they constitute about 60% of the population[64], integrate information across multiple olfactory channels. In the male CNS we annotated 71 types of uniglomerular ALPNs (284 neurons) and 111 types of multiglomerular ALPNs (409 neurons) as well as 6 ALON types (14 output neurons with distinctive morphology compared with classic ALPNs). Using a threshold of 5% input from pheromone ORNs (either directly or indirectly via dendro-dendritic synapses from other ALPNs) we identified 136 pheromone ALPNs (27 candidate PN types of which just 6 are uniglomerular), many which have not been functionally investigated (Fig 6e).

Consistent with our observations on visual and auditory processing, we see that dimorphism in the olfactory system emerges primarily in higher order neurons. Amongst all second order ALPNs, we identified just two sexually dimorphic types, one of which, the multiglomerular MZ_lv2PN, receives a complex mix of sensory inputs from pheromone and non-pheromone ORNs, as well as thermosensory neurons (VP3a+b). We found that the MZ_lv2PNs on each side of the brain consistently receive input from DA1 and VL2a glomeruli in males but not in females (Fig 6f), matching previous data implicating these neurons in male courtship behaviour[132]. Dimorphism of second order neurons is thus extremely limited. Instead most of the key transformations in dimorphic olfactory processing occur at the third order, where isomorphic projection neurons target sexually dimorphic and sex-specific downstream partners. Of the 182 ALPN types, 17 send at least 10% of their output to sex-specific or sexually dimorphic third-order lateral horn neurons in the male (Fig 6g). 12/17 are multiglomerular, and strikingly, half of these ALPNs are GABAergic vPNs, including the

uniglomerular VA1v vPN which sends more than 50% of its outputs to sexually dimorphic and sex-specific neurons. Connections from these isomorphic ALPNs are made primarily in the anteroventral lateral horn (LH), consistent with previous reports on pheromone representation in the LH[133], and indicating that pheromone-responsive ALPNs project to a region enriched for dimorphic edges in the connectome (Fig 6g).

We directly investigated this correlation between pheromone input and dimorphic/sex-specific outputs for all ALPNs (Fig 6h). Some pheromone ALPNs, including VA1v vPNs and DA1 lvPNs (M_lvPNm45)[134], are more likely to target sex-specific and sexually dimorphic downstream partners. Conversely, most ALPNs that receive little or no pheromone input do not make significant connections onto dimorphic or sex-specific downstream partners. Exceptions to these observations include M_vPNml67, which is enriched in dimorphic outputs despite minimal pheromone input, and uniglomerular pheromone-responsive PNs (DA1 lPNs, VA1v adPNs, and DL3 lPNs) which receive a high proportion of pheromone input but do not relay substantial output to dimorphic or sex-specific downstream partners. It is noteworthy that unlike most multiglomerular PNs, these uniglomerular PNs make strong connections in the mushroom body, the principal site of learning and memory[135–137]. We assessed the synaptic budgets from ALPNs to mushroom body Kenyon cells (KCs). Although there are differences in the proportion of connections of both pheromone and non-pheromone ALPNs onto the principal KC classes these may well be due to biological variability (Extended Data Fig 6e). A more detailed analysis of olfactory input to the mushroom body failed to find obvious sex differences (Pleijzier *et al.,* ms in prep) however there are notable changes in dopaminergic punishment and reward signals (Silva *et al.*, ms in prep).

To begin investigating the flow of pheromone information beyond the first two layers of olfactory processing, we followed the outputs of the excitatory uniglomerular ALPNs for pheromone-responsive glomeruli through the brain and into the VNC (Fig 6i). Our analysis reveals distinct processing streams downstream of pheromone detection, separating cVA-specific (LH007m) from pheromone-convergent (LH002m, LH008m, AL-AST1, LHAV1a1, CB3356,CB3359) pathways, confirming and extending earlier functional observations for some of these neurons[26,115]. While cVA contains information about a fly's sex and mating status, the ligands of VA1v and VA1d ORNs appear to be present in both sexes [125]. A dedicated pathway for cVA information that directly inhibits courtship song may be relevant for preventing courtship displays towards other males[100]. When this cVA information is integrated with other fly-derived odours, the descending pathways broaden, enabling flexible control of behaviour. This network analysis reveals how distinct pheromone combinations might activate unique patterns of descending neurons, enabling dynamic behavioural regulation. An in-depth analysis of the logic of pheromone processing will be presented elsewhere (Beckett, Morris *et al.*, ms in prep).

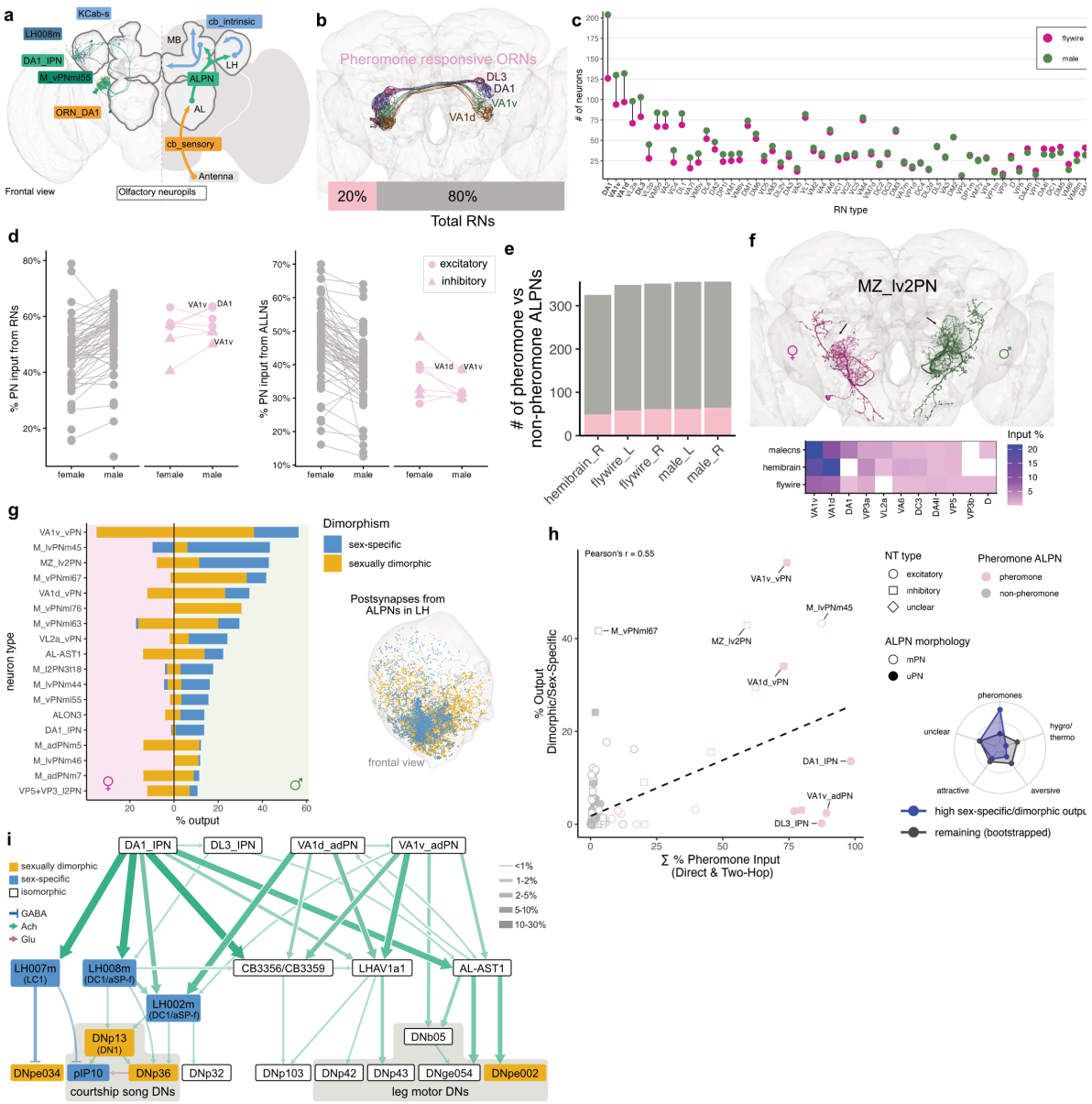

Figure 6 | Dimorphism emerges in the third-order of the olfactory system

a Illustration of the olfactory system describing flow of information from sensory neurons to the antennal lobe (`cb_sensory`) and from there to the lateral horn and mushroom body (`cb_intrinsic`) via antennal lobe projection neurons (`class: ALPN`). The left hand side shows example neurons, the right hand side shows the diagrammatic flow of information. AL: antennal lobe, LH: lateral horn, MB: mushroom body, PED: peduncle, CA: calyx. **b** Rendering of pheromone responsive ORNs: DA1, DL3, VA1d, VA1v. 10 neurons are shown for each type. Below, the percentage of pheromone RNs relative to all RNs. **c** Comparison of the number of RNs per type in the male (green) and female (FAFB/FlyWire: magenta) brains. The thermo/hygrosensitive glomeruli (VP1-5) are shown on the right of the plot. **d** Comparison of the percentage input to uniglomerular ALPNs in the male and female brains (FAFB/FlyWire) for pheromone (pink, distinguishing excitatory from inhibitory) and non-pheromone (grey) types. **e** Number of pheromone and non-pheromone ALPNs per side in the male and female brains. An ALPN is defined as being either from class ALPN or ALON and receiving at least 5% of its input from pheromone ORNs and their uniglomerular PNs. **f** One of two sexually dimorphic ALPN, MZ_lv2PN, in the male (green) and FAFB/FlyWire (pink). Below, a heatmap of its top RN input (over 0.1% per type) in the male and

female brains. **g** Left: ALPNs that provide at least 10% of their output to sex-specific or dimorphic neurons, in male or female brains. The plot shows percentage output in the male and female (FAFB/FlyWire) brains to dimorphic (yellow) and sex-specific (blue) neurons. Right: ALPN postsynapses of cell types shown in the plot, coloured by type of dimorphism. **h** Correlation analysis of the percentage of pheromone input for ALPNs (direct and one hop) versus the percentage output to dimorphic or sex specific neurons. Pheromone ALPNs in pink. On the right: Bootstrapped comparisons of sex-specific/dimorphic targeting across ALPN groups defined by dominant RN input valence. **i** Network diagram showing strong and selected downstream targets of the uniglomerular pheromone ALPNs (up to 2 hops).

Gustatory system

While volatile pheromones are detected by the olfactory system, non-volatile pheromones are detected by gustatory receptor neurons (GRNs) spanning the fly's mouth parts, legs, and wings[117]. Like olfactory pheromones, non-volatile pheromones influence sexually dimorphic behaviours in flies and they signal sex and species identity[138–140]. However, their actions are more localised, usually requiring physical contact for sensation as occurs when male flies tap and lick potential mates during courtship[141]. GRNs fall into six anatomically distinct subclasses based on their location: taste pegs, pharyngeal sensilla, and labellar bristles in the mouth; wing bristles; and two types of leg bristles (local and ascending) found on all three pairs of legs (Fig 7a). A detailed typing and cross-matching of all gustatory sensory neurons is reported in our companion paper[142]; combining this with identification and analysis of proboscis motor neurons reveals how sensory input is transformed into the motor programs underlying feeding and foraging behavior[143].

Foreleg gustatory sensory neurons are known to have dimorphic axon projections [144] but there otherwise appears to be minimal dimorphism in gustatory sensory neurons themselves [142]. However, there are clear differences in their downstream circuit organization. We began by identifying the proportion of sex-specific and sexually dimorphic downstream outputs for each GRN subclass (Fig 7b-c). Local leg bristles and wing bristles engaged most strongly with dimorphic circuits, with 11% of their downstream partners being either sex-specific or dimorphic in males; wing bristles also had a high fraction (6.2%) but ascending leg bristles (1.2%), pharyngeal (0.7%) and 0.5% labellar sensory neuron neurons were all much lower. Dimorphism in the initial processing of gustatory information therefore appears more pronounced in the VNC than the brain.

In the brain, dimorphic connectivity is concentrated in a specific subset of GRN types: 2/15 labellar bristle, 4/18 pharyngeal sensilla, and 2/9 ascending leg bristle types send >1% of their outputs to sex-specific or dimorphic partners in males. We observe a similar distribution in females, but different combinations of GRN types provide the majority of connections to dimorphic partners (Fig 7c). In contrast to the brain, 9/10 local leg bristle and all 4 wing bristle GRN types show dimorphic downstream connectivity (Fig 7c). These data suggest a clear anatomical division: information entering via diverse gustatory information channels associated with the mouth parts plays a broader role in directing general gustatory-driven behaviours like feeding, while a more specific set of receptors in the rest of the body may be more selective for sex-relevant cues.

We next compared the anatomy of sex-specific and dimorphic (green) versus isomorphic (black) second-order gustatory neurons in the male CNS (Fig 7d). The most connected isomorphic types downstream of pharyngeal sensilla and labellar bristles are largely restricted to the gnathal ganglion (GNG). In contrast, their dimorphic partners project further into the central brain and VNC, primarily targeting the leg neuropil T1 (LegNpT1), flange (FLA), anterior ventrolateral protocerebrum (AVLP), and superior medial protocerebrum (SMP) (Extended Data Fig 7b). Similarly, dimorphic partners of ascending leg bristle GRNs showed extensive innervation in the AVLP and superior neuropils (SMP, SIP, SLP). Dimorphic partners showed more pronounced T1 innervation downstream of ascending compared to local leg bristles. Among all subclasses, the top dimorphic and isomorphic partners downstream of wing bristle GRNs share the most anatomical similarity, with broad projections in the VNC and innervating the AVLP. Still, we find that the dimorphic partners project distinctly to the FLA. Taken together, these data reveal various neuropils involved in dimorphic taste processing in the male brain and ventral nerve cord. Neuroanatomical comparison of dimorphic and isomorphic second-order gustatory neurons in females showed similar results: female-specific mAL neurons downstream of labellar bristles, pharyngeal sensilla, and ascending leg bristle GRNs project to the superior lateral protocerebrum (SLP) and FLA, while second-order isomorphic populations are largely restricted to the the GNG (Extended Data Fig 7c).

We focused on leg and wing bristle GRNs to identify putative pheromone-responsive cell types. Using a combination of light microscopy images, connectivity clustering, and neurotransmitter predictions, we identified 9/10 local leg GRN types and all 3 wing GRN types as expressing one or a combination of ppk23, ppk25, IR52a, and IR52b receptors, each of which are known to be involved in male courtship behaviour[145–149]. See Beckett, Morris *et al.* (ms in prep) and Tastekin, Vicente *et al.*[125,142] for details. We matched 86% of local leg bristle GRNs and 75% of wing bristle GRNs to a receptor type (Fig 7e). We then queried the downstream partners of pheromone and non-pheromone GRNs to identify the ascending pathways for different taste information. Notably, two populations of ascending neurons, sex-specific AN09B017 and sexually dimorphic AN05B102, which include previously studied cell types vAB3[56,150] and PPN1[148], are strong targets of pheromone-responsive GRNs. A detailed analysis of the downstream circuits including integration of contact and olfactory pheromones will be presented elsewhere (Beckett, Morris *et al.,* ms in prep).

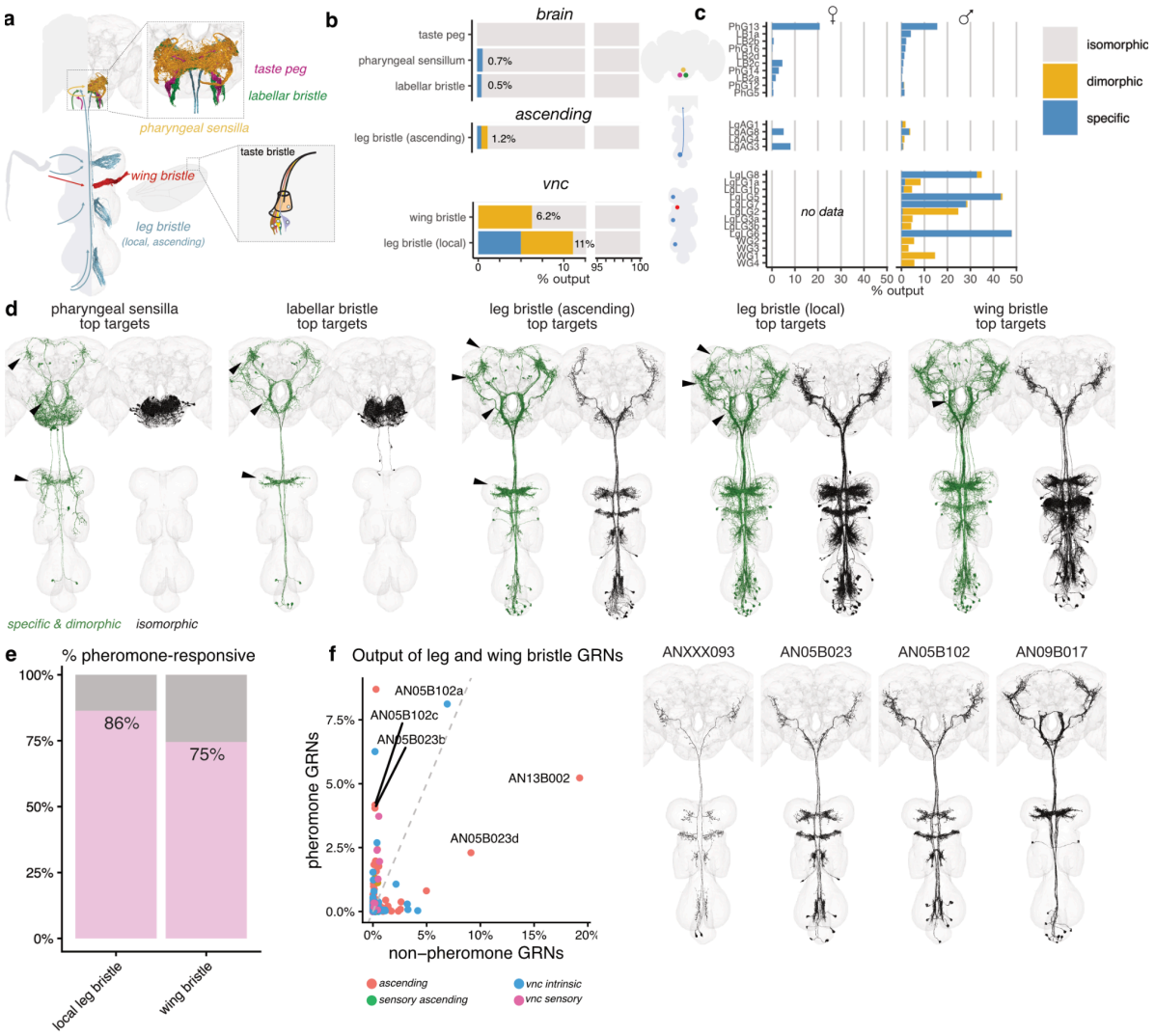

Figure 7 | Dimorphic second-order gustatory neurons separate contact chemosensation from taste

a Schematic representation (left) and 3D representation of taste sensory subclasses. Taste peg, labellar bristle, and pharyngeal sensilla GRNs (top inset) enter the nervous system via nerves targeting the brain; leg and wing bristle GRNs enter via the VNC. Bottom inset: schematic representation of taste bristle external structure. **b** Output-normalized proportion (%) of GRNs output to types annotated as sex-specific (blue) or sexually dimorphic (yellow) according to subclass and anatomical location: brain (top), ascending (middle), VNC (bottom). **c** For each subclass, the main GRN types targeting sex-specific and sexually dimorphic partners in females (left) and males (right).Types with >1% dimorphic outputs in either sex are shown. **d** Visualisation of the top ten sex-specific and sexually dimorphic (green) versus isomorphic (black) downstream partner cell types of taste sensory subclasses. Sex-specific and sexually dimorphic neurons extend distinct projections to AVLP, SMP, SLP, SIP, FLA, LegNpT1 (black arrows and Extended Data Fig 7c). **e** Input-normalized proportion of putatively pheromone-responsive versus non-pheromone responsive neurons in leg and wing GRN subclasses according to receptor-type mapping. **f** Left: Downstream partners of putatively pheromone-responsive and non-pheromone responsive local leg and wing GRNs, coloured by superclass. Percentages are output-normalized. Within-type connections are removed; Right: AN types proportionally stronger downstream of pheromone-responsive GRNs include ANXXX093, AN05B023, AN05B102, and AN09B017.

Global analysis of sexually dimorphic connectivity

Sex differences in behaviour could arise from unique circuit elements or the differential wiring of existing components. We have shown that the *Drosophila* nervous system consists of a combination of isomorphic, dimorphic, and distinct sex-specific cell types, suggesting that both mechanisms are likely at play. On average, 4% of an isomorphic male cell type's synaptic partners are either dimorphic or sex-specific. For dimorphic and sex-specific cell types, that percentage is much higher with 20% and 39%, respectively (Fig 8a; see Extended Data Fig 8a for female). Here we investigate how these dimorphic elements contribute to differences in wiring of the male and female central brain. We first develop a simple statistical approach to compare edges in the connectome graph. Even though this explicitly considers intra- and inter-individual variability we find that this approach must be augmented with knowledge about the nodes i.e. neurons and cell types in this graph in order to make robust conclusions.

A connectivity-based approach to find dimorphic edges

Connections to or from sex-specific cell types are, by definition, expected to be dimorphic as they cannot exist in the other sex. Connections involving dimorphic (but not sex-specific) types can be either isomorphic or dimorphic (Fig 8b). We further assume that most if not all edges between isomorphic cell types are isomorphic, and any differences between male and female are the result of biological variability and technical noise (reconstruction status, precision/recall of the synapse detection, etc). We first employ a purely connectivity-based approach to label individual connections as iso- or dimorphic. Because this approach is largely independent of the cell-type-level dimorphism annotations, we can contrast the results with expectations based on treating each neuron as sex-specific, dimorphic or isomorphic.

We treat the male and female (FAFB/FlyWire) brains as graphs in which nodes represent cross-matched or sex-specific cell types, and edges represent synaptic connections. Edges are weighted by the total number of synapses connecting the neurons of source and target types. As demonstrated in earlier work[31], synapse counts vary between datasets due to both biological and technical factors. To align edge weights for comparisons, we modeled the systematic differences between the male and female dataset using a simple principal component analysis (PCA). This yields a scaling factor of 0.581 which we apply to all male CNS edge weights for cross-dataset comparisons (i.e. there are more synapses in male CNS; see Extended Data Fig 8d). We assess edge dimorphism using a t-statistic where we take the mean difference between the (modeled) male and female edge weights, and divide it by a pooled standard deviation of the within-dataset (left vs right) weights (Fig 8c,d; see Methods for details). Intuitively, this means that connections with high within-dataset variability have to be very different between male and female to be flagged as significant. The p-values from this analysis were false discovery rate (FDR) corrected using the Benjamini-Hochberg procedure[151].

Across all 3.74M edges between cross-matched neurons in the central brain, we find 381k edges (10%) with significant (FDR-corrected $p <= 0.1$) male-female differences, 182k (4.9%) of which are highly significant (FDR-corrected $p <= 0.01$). This pool of candidate dimorphic

edges includes a number of edges with small but very consistent male-female differences. We therefore additionally apply a threshold of at least 30% difference which reduces the number of candidate dimorphic edges to 378k. As demonstrated previously[31,152], we find that weak isomorphic connections are unstable: around 60% of single-synapse connections in one hemisphere are not at all present in another hemisphere from either the same or another brain (Fig 8e). To achieve a 90% probability of an edge in the male also being present in the female dataset, it needs to consist of >10 synapses. In the opposite direction, that threshold is >7 synapses – likely due to the generally stronger edges in the male CNS. We consider edges below these thresholds to be unreliable and treat them as noise. Because edge weight distribution is heavily skewed with many weak edges (Extended Data Fig 8b), around 80% of all cross-matched edges fall below these thresholds. Crucially though, the remaining above-threshold edges collectively contain 90% of all synapses in the male (88% in female) (Fig 8f; Extended Data Fig 8f).

Contrasting morphology- and connectivity-based approaches

Having labeled individual type-to-type edges as either dimorphic, isomorphic, or noise independently of the neuron-level dimorphism annotations allows us to compare the results (Fig 8g, Extended Data Fig 8g) to the expectations (Fig 8b). Discounting noisy connections, only around 1 in 5 (22.9% or 5.4k) edges involving dimorphic (but not sex-specific) cell types are themselves dimorphic. By contrast, 68.2% (31.6k) of edges involving sex-specific neurons are flagged as dimorphic. Because these edges can – by definition – not exist in the other sex, the remaining 31.8% are labeled as isomorphic due to high left/right variability. We consider these to be false-negatives and treat them as dimorphic.

Conversely, around 1 in 10 edges (11% or 72.2k) between isomorphic types are significantly different between male and female. It is possible that some of the types involved evaded our initial neuron-level search and should have been labeled as dimorphic. However, a review of the 500 isomorphic types that showed up most frequently only led to a small number (<5) of changes in dimorphism status. For the remainder, male-female differences in connectivity could often but not always be tracked down to segmentation issues or uncertainties with respect to cell type boundaries. While we cannot rule out the possibility that morphologically isomorphic neurons form dimorphic connections with each other, we would require additional connectomes to either confirm or refute such connections as genuinely dimorphic. We therefore consider these edges to be false-positives and treat them as isomorphic. Our account therefore represents a conservative lower bound for the extent of dimorphism in the brain.

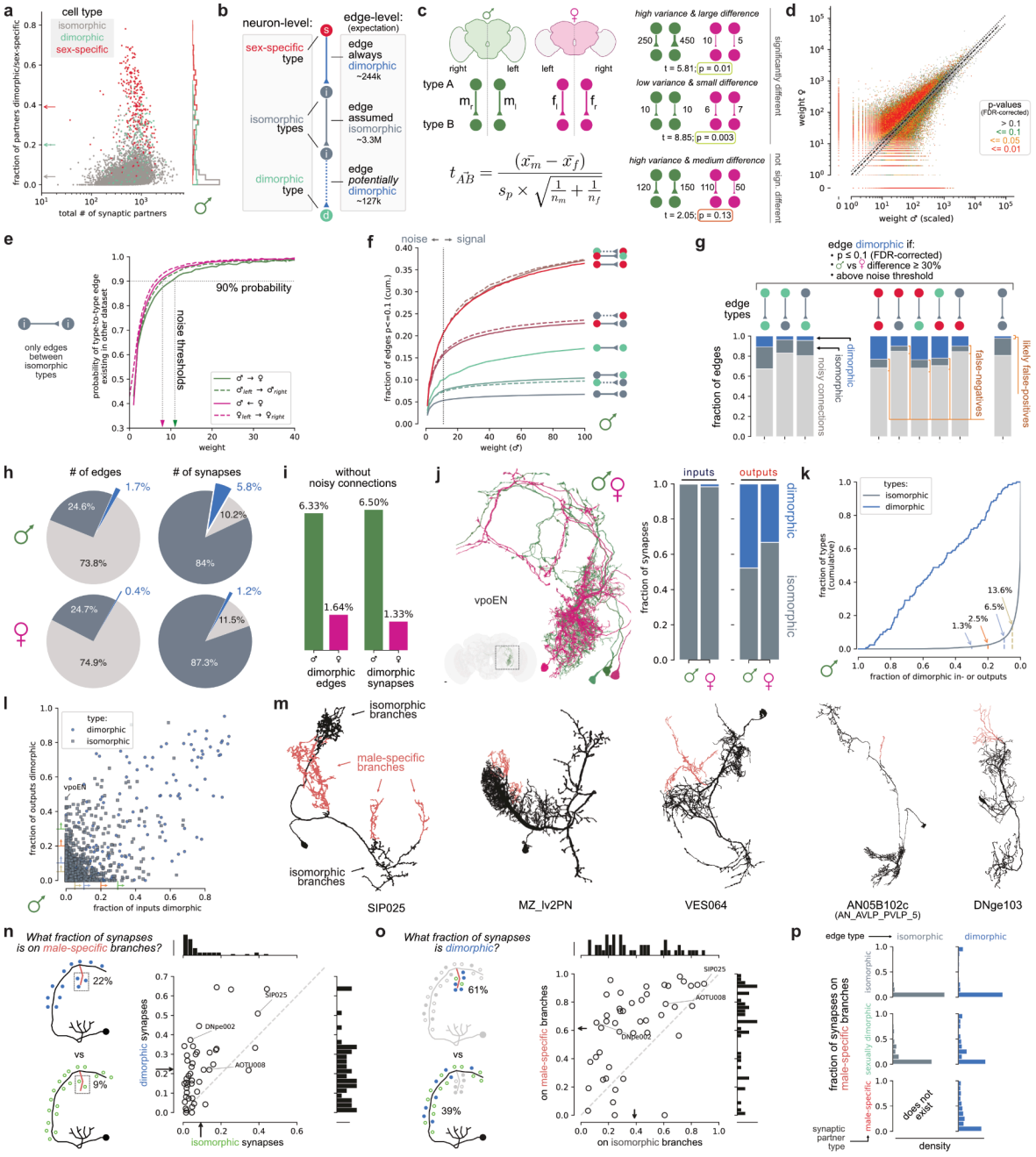

Figure 8 | Sexual dimorphism in brain connectivity

a Dimorphic up- and downstream synaptic partners as a fraction of total synaptic partners for all cross-matched male cell types. Arrows on the y-axis indicate means for iso-, dimorphic and male-specific types. **b** Illustration of neuron-level dimorphism and expected resulting edge dimorphisms. **c** Explanation of t-statistics used to find edges significantly different between male and female. See Methods for full definition. **d** Male (scaled) vs. female type-to-type edge weights coloured by false discovery rate (FDR)-corrected p-value. Dotted envelope demarcates a 30% difference in connection weights. **e** Probability of finding an isomorphic edge of a given weight in another hemisphere of the same or different dataset. **f** Cumulative fraction of male edges with FDR-corrected p-values below 0.1 per edge type. Dotted vertical line marks 90% probability threshold from e. **g** Fraction of dimorphic, isomorphic and noisy connections (male + female) broken down by edge type. False-positives and -negatives are labeled based on expectation as laid out in a. **h** Proportion of edge types by total number and by synapse count in males (top) and

females (bottom). False-positives and -negatives (g) were re-assigned to isomorphic and dimorphic edges, respectively. Same colours as g. **i** Fraction of dimorphic edges/synapses not counting noisy connections. **j** Example of an isomorphic cell type (vpoEN) with a large fraction of dimorphic outputs (by synapse count) in both male and females. **k** Fraction of iso- and dimorphic types with at least X% dimorphic in- or outputs (by synapse count) in male. **l** Fraction of dimorphic in- versus outputs (by synapse count) per cell type in the male. Arrows correspond to labeled thresholds in panel k. **m** Examples for the 46 dimorphic cell types that were split into isomorphic and male-specific branches. **n** For each split type, the fraction of total synapses from isomorphic and dimorphic connections found on male-specific branches. **o** For each split type, the fraction of synapses on male-specific and isomorphic branches that contribute to dimorphic connections. Arrows on graphs in m and n indicate the means along the respective axes. **p** For each edge from/to a split type, the fraction of synapses found on male-specific branches broken down by dimorphism of the synaptic partner (rows) and edge columns).

A significant proportion of the brain is directly or indirectly dimorphic

We find that 1.7% of edges in the male and 0.4% of edges in the female central brain are dimorphic (Fig 8h). Total edge counts are dominated by weaker edges: almost 60% of all type-to-type edges consist of 3 or fewer synapses but they collectively contain only 5% of all synapses. Therefore, a better metric is the fraction of synapses contributing to dimorphic connections: in the male 5.8% of all synapses are part of dimorphic connections versus 1.2% in the female. Discounting noisy connections, the proportion of dimorphic synapses rises to 6.5% in males and 1.3% in females (Fig 8i).

Next, we investigated the fraction of isomorphic cell types in the brain that receive or send significant dimorphic connections. For example, the morphologically isomorphic cell type vpoEN, a pair of auditory neurons which have previously been shown to be involved in courtship[51], has 47.7% dimorphic outputs and no dimorphic inputs in males (33.2% and 1.6% in females, respectively) (Fig 8j). These neurons represent an example of how isomorphic circuit elements can wire differently in males versus females, thereby contributing to dimorphic circuits. Historically, neurons such as these have been described as being themselves dimorphic, e.g. by virtue of responding differently to the same stimulus in males and females. Here, we distinguish between primary dimorphic neurons that exhibit clear morphological differences (e.g. AOTU008), and “secondarily dimorphic” neurons like vpoEN, which present as isomorphic but have a significant fraction of dimorphic in- or outputs. Around 1 in 7 (13.6%) isomorphic cell types in the male central brain receive at least 5% dimorphic in- or outputs (Fig 8k,l), compared to 5.5% in the female (Extended Data Fig 8h,i). In combination with primary dimorphic (1.5%) and sex-specific types (3.5%), this renders 17.9% of the male central brain directly or indirectly dimorphic. Due to the lower number of sex-specific types (0.8%), that percentage drops to 7.8% for the female.

Correlation between dimorphic morphology and connectivity

We previously described cases where morphological changes (extra male-specific branches) correlate well with dimorphic connectivity (DNpe002 in Fig 4f; Extended Data Fig 4Ac), as well as cases where the correlation is less consistent (AOTU008 in Fig 3e-g). Having defined dimorphic edges across the central brain, we expanded on these anecdotal observations and looked at the morphology-connectivity correlation for a larger pool of samples. Of the ~120 dimorphic cell types, 46 types (135 individual neurons) with well-defined extra axonal or dendritic branches in the male were split into the isomorphic and male-specific parts (Fig

8m). For each connection to or from these types (4,418 isomorphic and 1,856 dimorphic edges), we determined the number of synapses on male-specific versus isomorphic branches. On average, male-specific branches contain 22.2% of all dimorphic synapses and only 9.2% of all isomorphic synapses (Fig 8n). Here, the mean for isomorphic synapses is skewed by a small number of types with large male-specific branches (e.g. SIP025) that contain a high fraction of isomorphic synapses. The median is 20% for dimorphic and only 4.8% for isomorphic synapses. Conversely, 61% of synapses on male-specific branches are dimorphic and 39% are isomorphic, compared to 39% and 61% on isomorphic branches, respectively (Fig 8o). Again, this mean is skewed by a small number of outliers: male-specific branches of DNg83, DNbe005 and DNge128 contain little to no dimorphic synapses, suggesting that their male-specific branches are either the result of biological variability or not the primary driver of dimorphic connectivity. Importantly, for 32 out of the 46 analysed types, the male-specific branches carry mostly dimorphic synapses. These findings suggest that sex-specific branches tend to be enriched in dimorphic connectivity, but the opposite is not necessarily true: dimorphic in- or outputs can be found across the entire neuron. Only a small fraction of dimorphic connections are localised exclusively to sex-specific branches (Fig 8p).

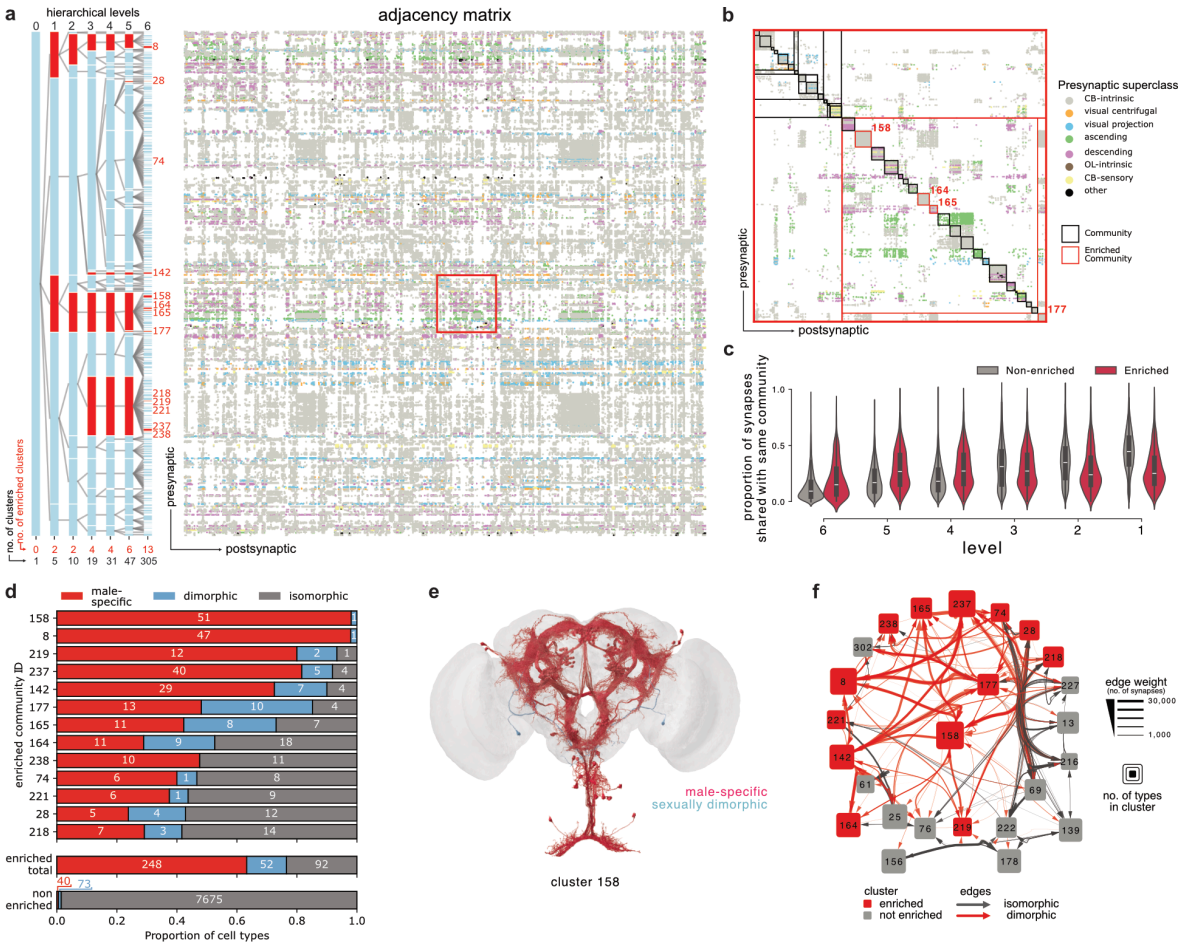

Figure 9 | Sexual dimorphism in brain networks

a Hierarchical community detection partitions the cell types of the male central brain into blocks of similar connectivity. Clusters at 6 different levels of the hierarchy (left) are derived from the cell-type-to-cell-type connectivity matrix (right). The IDs of male-enriched clusters are shown in red. **b** Zoom-in on inset highlighted in panel a showing the hierarchical partitions in the adjacency

matrix, with clusters enriched with non-isomorphic types in red. Rows are coloured by superclass. **c** Proportion of within-community synapse counts across the hierarchical levels. **d** Breakdown of cell type identity in the 13 enriched clusters at level 6. **e** Visualisation of enriched cluster 158, the most statistically overrepresented for male-specific or dimorphic cell types. **f** Network graph of the neighbourhood (≥1,000 synapse threshold) around enriched cluster 158.

Dimorphic neurons are strongly clustered and interconnected

Having defined both individual dimorphic cell types (nodes) and connections (edges) across the connectome graph, we next investigated the organisational logic of these elements across the whole connectome graph. Starting from the type-to-type graph for the male central brain, we obtained hierarchical community partitions, recursively grouping nodes into clusters of similar connectivity (Fig 9a,b; see Methods for details). This analysis identified two key modes of involvement of the dimorphic and male-specific types in the network structure.

First, only 13 out of 305 clusters were statistically enriched for dimorphic or male-specific types, constituting 300 of 413 (72%) non-isomorphic types. The enrichment persisted over six hierarchical levels, where 2 clusters remained statistically enriched even at the top level. On average, male enriched clusters connected more densely within their community than cell types in non-enriched clusters across hierarchical levels 6-4 (Fig 9c). This emphasizes that the majority of dimorphic/sex-specific types contribute to globally distinct subnetworks, and that male-specific cell types are the main contributors to this enrichment (Fig 9d). In contrast, the remaining 113 male-specific and dimorphic types were sparsely distributed across 64 non-enriched clusters; this population is highly integrated into the isomorphic subgraph.

The most enriched cluster (158) contains many male-specific cell types, including some (but not all) P1 subtypes (Fig 9e). A detailed analysis of the P1 neurons in the male CNS connectome is presented elsewhere (Rubin *et al.,* ms in prep). Upon inspection of the cluster 158 neighbourhood, we found that the other 12 enriched clusters connect to cluster 158 with at least 1,000 synapses, mainly via male-specific connections (Fig 9f). This cluster exemplifies a second key organisational: male-enriched clusters connected to an average of 8.5 other enriched clusters by at least 1,000 synapses, compared to 1.1 for non-enriched clusters. Together, these findings suggest that the male-specific subunits of the connectome connect densely within each cluster, and that individual clusters are globally interconnected with other male-specific communities. This is strongly reminiscent of the long-standing hypothesis that *fruitless* expressing neurons may preferentially connect with each other to form circuits regulating male courtship[129].

Discussion

The complete connectome of the *Drosophila* male central nervous system represents a major step forward in the quest to link neural circuits and behaviour. The fully proofread connectome enables end-to-end analysis from eyes to legs. Our rich annotations link over 95% of neurons to previously reported cell types and to functional analysis in the literature.

The number of sex-specific and dimorphic neurons is relatively modest, approximately 5% of the male brain and ~2% of the female brain, but it is clear they can have major impacts on function. At the cellular level, perhaps surprisingly, we find male-specific neurons to be more common than dimorphic neurons (which have altered morphology), whereas the opposite is true in females. A greater proportion of male-specific versus female-specific neurons is also observed in *C. elegans* although the difference is more extreme (23.6% vs 2.6%)[153]; this consistent bias may reflect selection pressure on male behaviours.

We clearly demonstrate that sexually dimorphic elements are not evenly distributed in the brain but are concentrated in higher brain areas. This is compatible with early observations of the pattern of *fruitless*-expressing neurons in the brain[129,154] as well as volumetric differences between male and female brains[60]. However, we can now place these neurons in circuits. We see that they are in deep layers of the connectome between the sensory and motor periphery (Fig 3l). This suggests a hierarchy in which sex differences primarily modify integrative and decision-making areas while sensory detection and the highly tuned motor interface remain more constant. This logic appears distinct from *C. elegans,* where male-specific neurons are principally associated with circuits local to its dimorphic genitalia[153]. It will be very interesting to see which of these patterns apply to circuit evolution across species[155].

Even within higher brain centres, there is additional structure: dimorphic neurons form synapses in a spatially clustered fashion (Fig 3k) and this can be associated with feedforward and feedback connections in particular sensorimotor pathways such as the visual elements in Fig 4g or the ascending taste neurons in Fig 7d. Sex-specific neurons contribute to multiple wiring motifs including sign inversion by inhibitory interneurons downstream of visual projection neurons (e.g. VES200m, Fig 4n) and switches in partner connectivity (e.g. PVLP207m, Fig 4e,n). In contrast, some sex-shared interneurons appear to act as a node for dimorphic connectivity without showing any sign of dimorphic morphology (vpoENs in Fig 5b,c). Zooming out, we see that the large majority of male-specific/dimorphic neurons form a small number of tightly coupled hubs (Fig 9). While some dimorphic neurons do integrate more sparsely across the connectome, the dominant organisational principle seems to be modules of sex-specific circuits. From an evolutionary perspective it may be easier to evolve such discrete modules in order to produce major changes in sex-specific behaviour. This is also consistent with our observations that the majority of sex-specific and dimorphic neurons originate from a small number of neuroblast lineages (Fig 3j).

We observed a strong correspondence between *fru* and *dsx* expression and dimorphic and male-specific neurons. However, there were potentially interesting discrepancies. Over 1,500 *fru*/*dsx* positive neurons were not dimorphic in the connectome; although technical limitations may play a role, this does raise the possibility that they are regulating factors other than wiring. To give a concrete example, we can confidently assign the cell type LHPV6q1 (pSP-e, FMRFa-WED). It has documented sex differences in its electrophysiological properties including its spontaneous firing rate[50], but shows no wiring differences in the connectome. Conversely, we observe many neurons where *fru*/*dsx* expression is absent but neurons are dimorphic or sex-specific. Although technical limitations likely account for some of this discrepancy, we can be quite confident in some

cases (e.g. 236 neurons in the central brain with known lineage) leaving open the possibility that alternative mechanisms are at play.

Connectomics is now in a rapid growth phase, but comparative connectomics is still in its infancy. Low sample numbers still pose significant challenges. Lessons learned during this project leave us cautious in some areas but still optimistic overall. We believe that attempts to extract biological differences from direct comparison of two raw connectome graphs are unlikely to be successful. Rather it is first necessary to convert this to a cell type graph, capturing the fundamental unit of conservation across connectomes while accounting for interindividual variation[31]. A strong quantitative understanding of that variability (and its technical and biological origins) is also essential. Crucially, we found that considering bilateral consistency of cell type morphology and wiring enabled us to draw robust conclusions about the identity of dimorphic elements. A specific example may be instructive. We previously noted that a visual projection neuron (LoVP109/LTe12) present with one exemplar in each optic lobe of the FAFB female brain[30,31] could not be found in the single male optic lobe reported in Nern *et al*[36]. However, we now find this cell in the second optic lobe of the complete male CNS dataset, suggesting a developmental error in the first optic lobe. We estimate this error rate at <1% for neurons in each hemisphere[31]; if errors occur independently in the two hemispheres – as observed here – then the chance of missing an entire cell type is <0.01% or about 3 pairs of neurons in the central brain; this is a very low false positive rate compared with our observation of >1,000 male-specific neurons. Similar principles apply for connectivity, echoing recent work on cross-species comparisons of the larval *Drosophila* olfactory system[156]. Nevertheless, we found that expert curation was required to separate biological signal from cases of technical noise (which is more commonly correlated across both sides of one brain).

Although this is the largest finished connectome to date, limitations remain. First, while our dataset includes the entire male CNS, we were only able to make comprehensive comparisons to the FAFB female brain[30,31,41]; comparisons to the partially proofread female nerve cord (FANC) dataset[35,157] were necessarily more restricted. This limitation could be removed by the very recent release of the female Brain and Nerve Cord (BANC) dataset[158]. Although BANC remains a work in progress at the time of writing, the nerve cord is at a more advanced stage and should therefore allow male-female comparisons; nevertheless, we would caution that careful joint cell typing and a quantitative understanding of variation will be essential to draw robust conclusions about sex differences. We see huge value in integrative approaches to connectome analysis and we already provide powerful tools (https://natverse.org/coconatfly) that enable analysis across all publicly available fly connectomes including the BANC and male CNS.

Second, the connectome provides the structural wiring diagram, but of course functional analysis will be required to confirm predictions about differences in information flow and their impact on behaviour. We are heartened by the recent success of brain-scaled simulation studies [159,160]. In the near future manipulation of neuronal connectivity and activity *in silico* may be used to understand the impact of the dimorphic elements we observe and to prioritise the many experimental hypotheses that emerge from connectome analysis.

Finally, the connectome represents the end state of a complex but highly stereotyped process of development. In some cases we may have failed to identify developmentally

homologous neurons because their structure and connections are too divergent. Integration with molecular and developmental studies may be essential to resolve these issues[68,69,161]. However, it does provide the most detailed picture yet of the result of sexually dimorphic development and this should prove invaluable for studies examining the molecular specification of brain wiring[162]. Similarly, this connectome represents a snapshot in the lifetime of an animal. This study confirmed our previous observations that the majority of the wiring diagram is stable[31]. However, even strongly innate dimorphic behaviours can be modified by experience[163,164]. Building on developments in comparative connectomics – including this study – there will be exciting opportunities to learn about the footprint that experience leaves in the wiring diagram of the brain.

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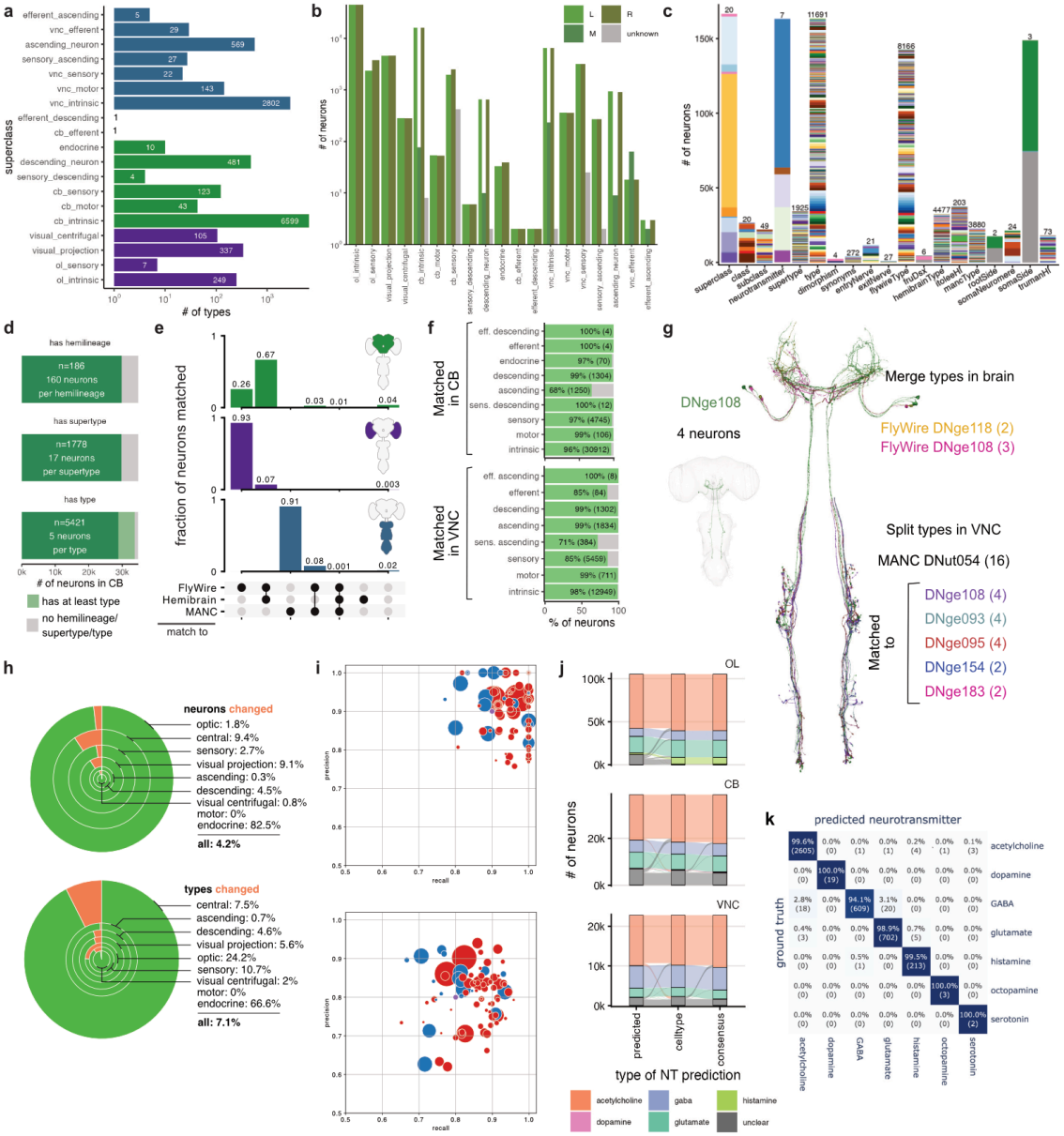
Author Contributions

KJH & ZL prepared the sample. WQ, AC, CSX & HFH imaged the sample. SP, ETT, TPi & SS aligned the EM data. SB, MJ & CO produced the automated segmentation. IRB, MC, ECM, S-yT, AMCF, MiC, MG, CO, TPa, FeL, BJM, IA, PB, BSC, IdHV, CRD, SFM, MAF, IH, GPH, LK, JK, SAL, ML, AL, CAM, IM, CM, EM, NO, AP, BP, EMP, AR, JRS, RJVR, ALS, LAS, LSC, CS, ST, AT, JJW, HW, EAY & TY proofread the segmentation. GBH & CO produced the automated synapse detections. SB, AN, DA, GBH & ASB identified neurotransmitters. PSc, AN, JB & SC developed spatial transforms. IRB, MC, PSc, ECM, AN, S-yT, AMCF, MG, TS, CRW, FeL, BJM, MWP, VS, GB, PB, BC, IdHV, GD, ED, MdS, CRD, KE, LK, MM, IM, EM, AP, AR, IT, HW, CR & GSXEJ typed and annotated cells. SB, IRB, MC, PSc, ECM, AN, S-yT, AMCF, MiC, MG, CO, TPa, TS, KDL, CM, CK & GSXEJ provided quality control. SB, PSc, SP, WTK, ETT, LEB, JH, FrL, JC, PMH, DJO, RS, LU, AZ, SS & GSXEJ developed software tools. SB, IRB, PSc, AMCF, LEB, FrL, PMH & EMR developed visualizations and presentation tools. IRB, MC, PSc, MJ, AN, AMCF, ASC, MBR, GMR & GSXEJ wrote the main text. SB, MC, PSc, AN, SP, ASC, DA, GBH, JH & MBR wrote the methods. SB, IRB, MC, PSc, AN, AMCF, ASC, MG, GBH, FK, TS, CRW, VS, YY, MD, SSM, EMR, PSe, AZ, MBR & GSXEJ analyzed the connectome and designed figures. MC, PSc, ECM, GWM, SR, SS, MBR & GSXEJ provided supervision. VJai, WK, SW, GMC, GMR & GSXEJ acquired funding. SB, SP, SMP, RG, VJay, WK, JF, LKS, GMC, HFH, GMR & GSXEJ guided the project.

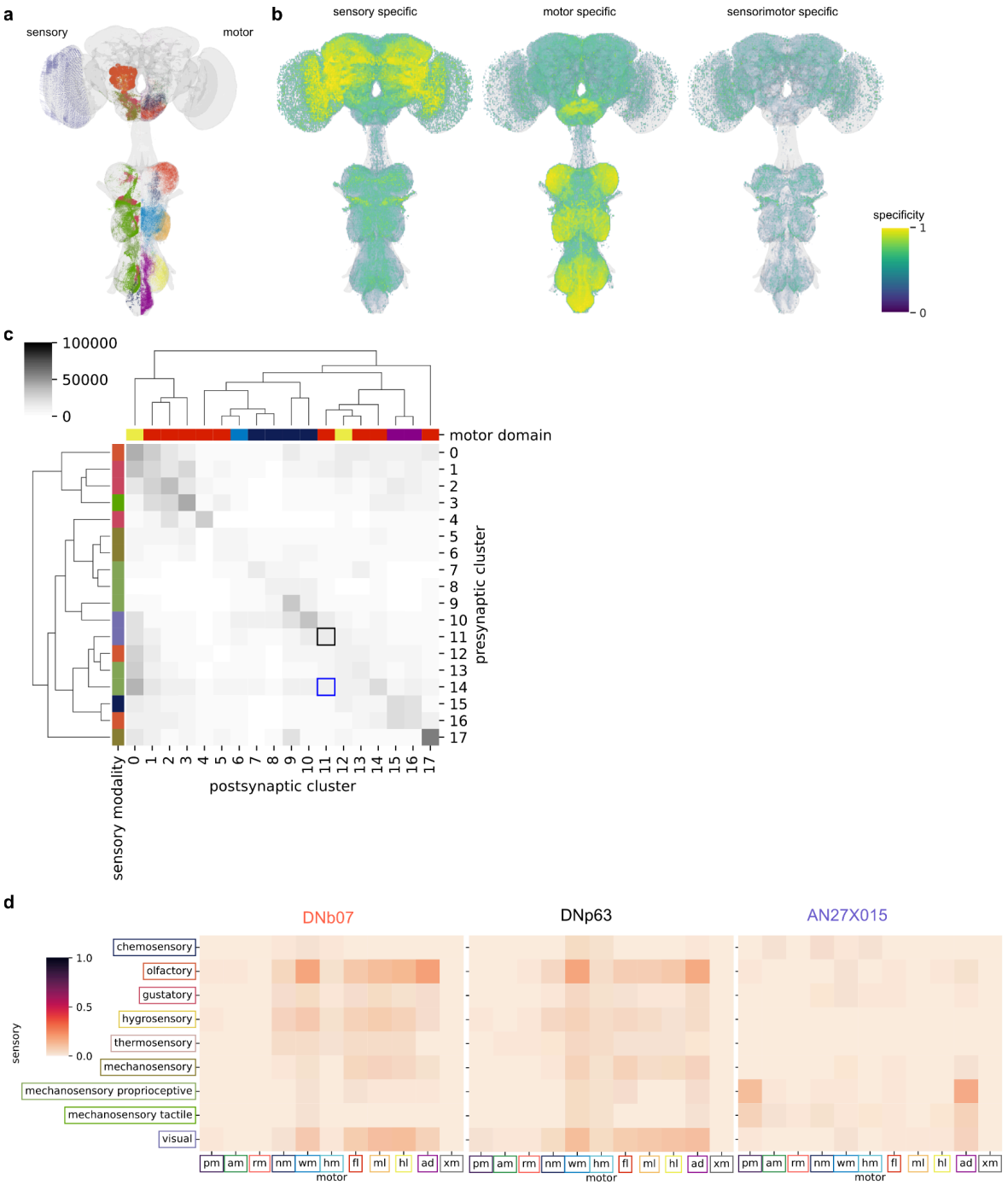
Extended Data Figures



Extended Data Figure 1 | Annotation, cross-matching and synapse and neurotransmitter assignment, related to figure 1 and extended data figure 9

a Number of types per superclass and per CNS region. **b** Number of neurons by soma or root side per superclass. **c** Number of neurons with annotations for several categories.The number of unique annotations for each one is shown at the top of the bar. **d** Number of neurons in the central brain with `itoleeHl`, `supertype` and/or `type` annotations. The number of distinct annotations, and the average number of neurons per category is shown in the bar. **e** Fraction of neurons cross-matched to existing datasets per CNS region. **f** Number of cross-matched neurons in the central brain and VNC, per superclass. The number of matched neurons and the corresponding percentage is shown. **g** The descending neuron type DNge108 was matched to 2 types in FAFB/FlyWire and a subset of neurons for type DNut054 in MANC. The remaining 12 neurons in DNut054 match 4 other types in male CNS. **h** FlyWire cell types updated via cross-matching with the male CNS broken down by superclass. Top: percentage of neurons for which the type changed; bottom: percentage of

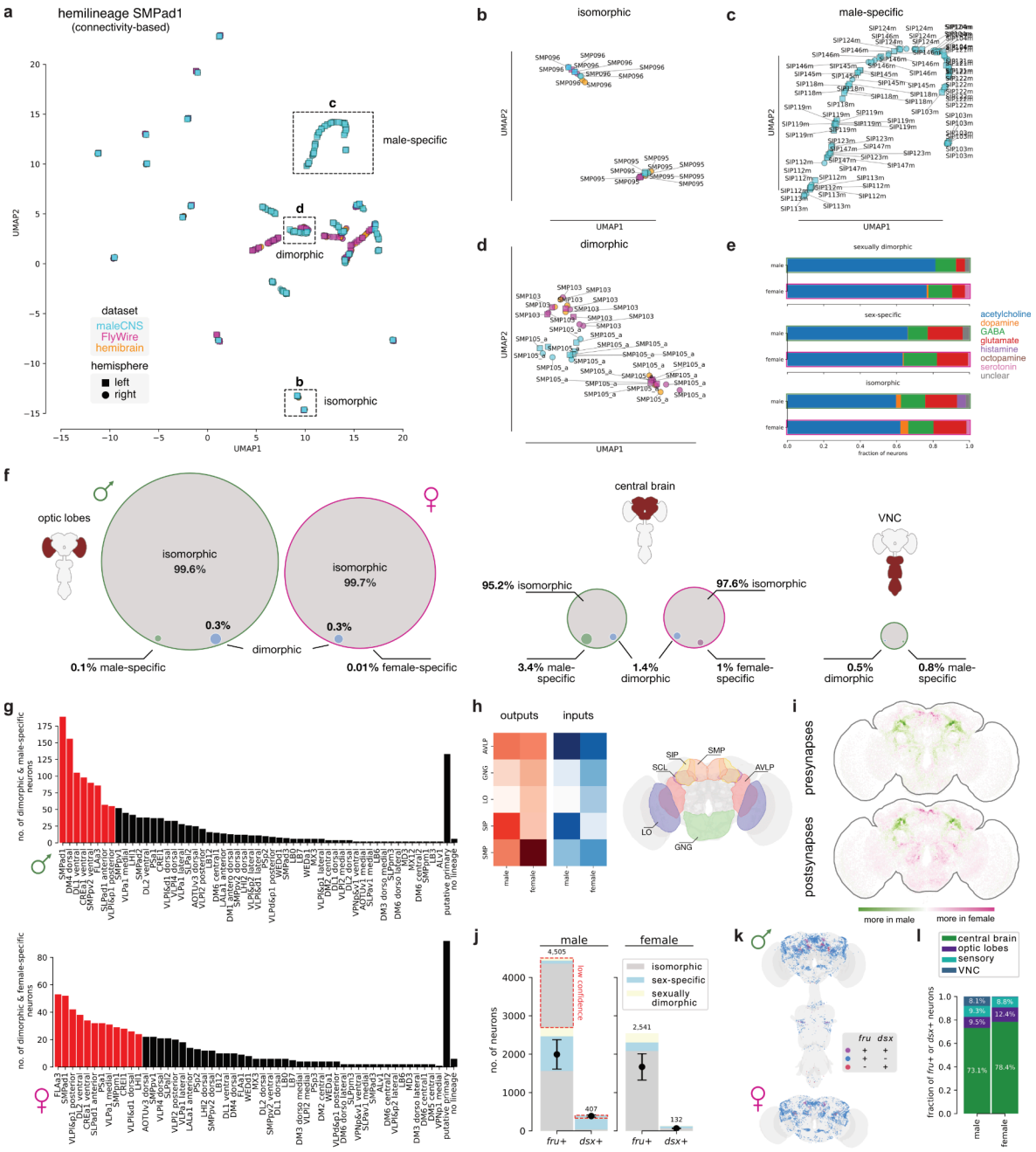
types for which at least one neuron changed. Surface area of wedges corresponds to the total number of neurons/types in that category. **i** The precision and recall of synapse T-bar predictions (top) and pre-post connections (bottom) in each region of interest (ROI). Markers are scaled by ROI size and color differentiates between brain (red) and VNC (blue) neuropils. **j** Change in neurotransmitter prediction for `predictedNt`, `celltypeNt` and `consensusNt` for each neuron in the CNS subregions. **k** Neuron-level confusion matrix for neurotransmitter prediction (`predictedNt`) on the held-out test set.



Extended Data Figure 2 | related to figure 2

a Synapses from sensory (left) or motor groups (right) in the CNS. **b** Maximum intensity projection of synapses of neurons in the CNS that are specialised in flow for left: sensory group, middle: motor group, right: specific sensory-to-motor pairings. **c** Connectivity between clusters in Fig 2h clustered by

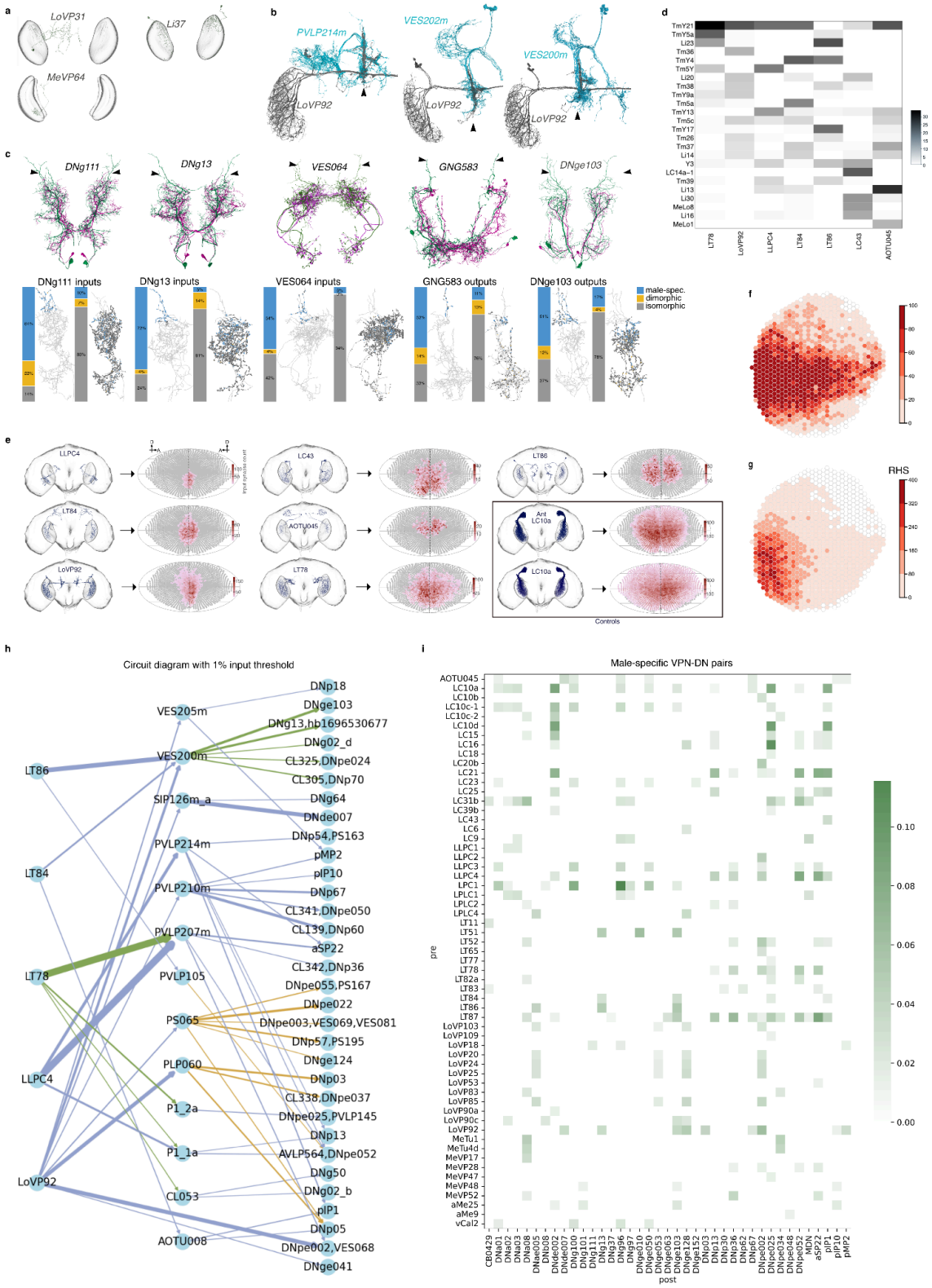
cosine similarity. Mode preferred sensory modality and motor domain are labeled. Black and blue highlights indicate the elements containing the DN-DN and AN-DN connection in Fig 2m, respectively. **d** Sensory-motor flow for the neck connective types in Fig 2m.



Extended Data Figure 3 | Additional dimorphism analysis, related to figure 3

a UMAP embedding of connectivity-based cosine distance for neurons of the SMPad1 hemilineage from three connectomes/five hemispheres: male CNS, FlyWire and hemibrain. **b-d** Zoom-ins on insets labeled in a showing isomorphic (b), male-specific (c) and dimorphic (d) cell types. **e** Distribution of predicted neurotransmitters for dimorphic, sex-specific and isomorphic neurons. **f** Pie charts showing the fraction of dimorphic and sex-specific neurons across optic lobes, central brain and VNC. Relative sizes correspond to the number of neurons. Note that VNC dimorphism labeling is partial and hence represents a lower bound. **g** Number of dimorphic and sex-specific neurons per

hemilineage in male (top) and female (bottom). Lineages coloured in red collectively produce ≥50% of dimorphic and sex-specific neurons. **h** Top 5 neuropil with the most dimorphic/sex-specific synapses. **i** Difference between distribution of dimorphic/sex-specific synapses in males and females. **j** Breakdown of *fruitless* (*fru*+) and *doublesex* (*dsx*+) annotations by dimorphism. Dotted red outline indicates low-confidence annotations in the male. Pointplots in black represent mean and standard deviation of expected counts based on prior literature. **k** Cell bodies of *fru*+ and *dsx*+ neurons in male (left) and female (right). **l** Distribution of *fru*+ and/or *dsx*+ neurons across main brain regions.



Extended Data Figure 4A | Additional visual system analysis, related to figure 4

a Unmatched outlier types not considered male-specific because not left-right symmetrical. Note that Tm40 is currently classified as isomorphic. However, FAFB/FlyWire has lower cell count compared to the male CNS (41 vs 180 ids). Consequently, it was excluded from the analysis

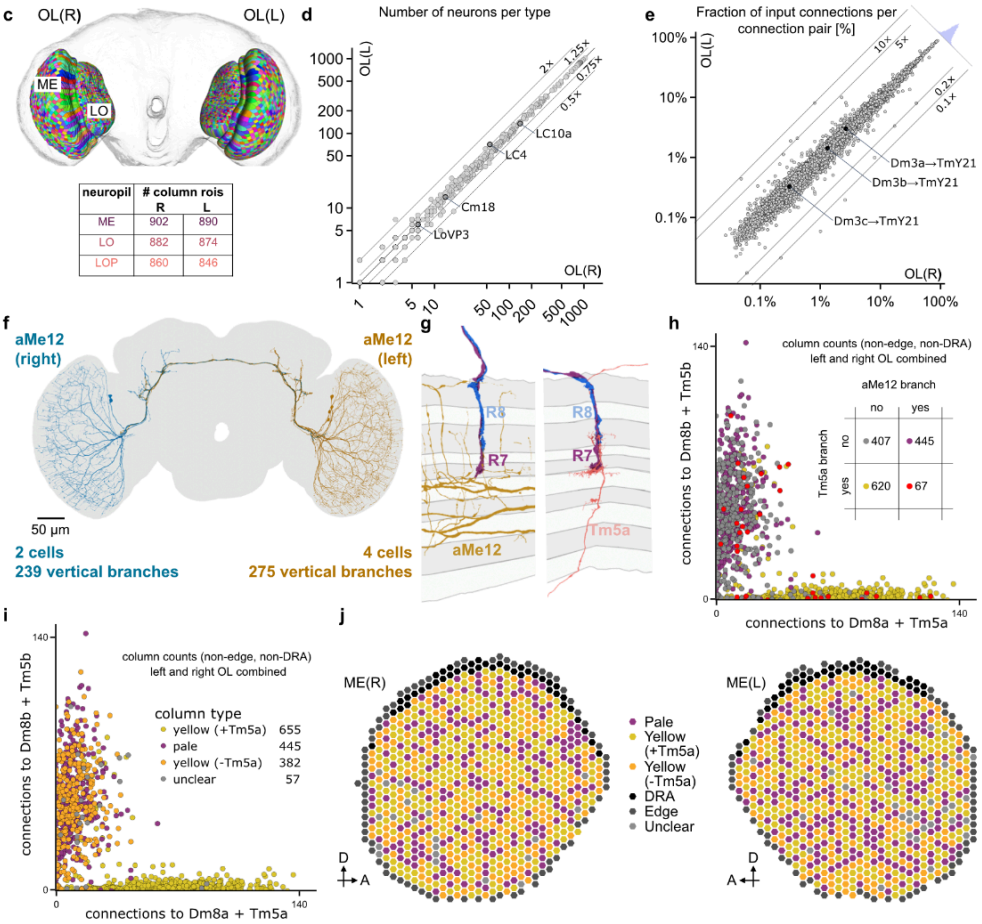
shown in Fig 4c,l. **b** Male-specific types converging on the male-specific node defined by LoVP92 axons. **c** Dimorphic types converging on the male-specific node defined by LoVP92 axons. Stacked bar charts indicate the proportion of dimorphism status among connection partners of the dimorphic types. **d** Heatmap showing the strongest inputs from optic lobe intrinsic neurons to frontally-biased VPNs. **e** Examples of frontally-biased VPNs. Spatial coverage heatmaps show input synapse distributions mapped onto a Mollweide projection of the right compound eye's visual field. Color scale bars show input synapse count. **f** Spatial map showing all inputs to TmY21 in the ME. **g** Inputs to male-specific, dimorphic and secondary dimorphic frontal types are biased towards columns devoted to the frontal field of view. **h** All pathways from VPNs in Fig 4l, to DNs with known functions or sexual dimorphism, within two synaptic hops, where all connections are stronger than 1% input. **i** Effective connectivity based on male specific pathways, involving at least one dimorphic or sex-specific cell type, within two synaptic hops, where each connection is stronger than 1% input, from all VPNs, to DNs with known functions or sexual dimorphism. The colour is based on the sum of direct connection strength, and the square root of the products of weights in the two-hop pathways.

a

groups	# cell types		# cells		# input conn		# output conn	
	R	L	R	L	R	L	R	L
ONIN	149	149	15.7K	14.4K	8.3M	7.3M	15.3M	15.4M
ONCN	95	95	32.4K	32.3K	13.9M	11.6M	27.6M	28.1M
VPN	352	348	4.5K	4.5K	6.0M	5.1M	9.9M	10.1M
VCN	104	104	267	273	776.1K	757.2K	2.5M	2.7M

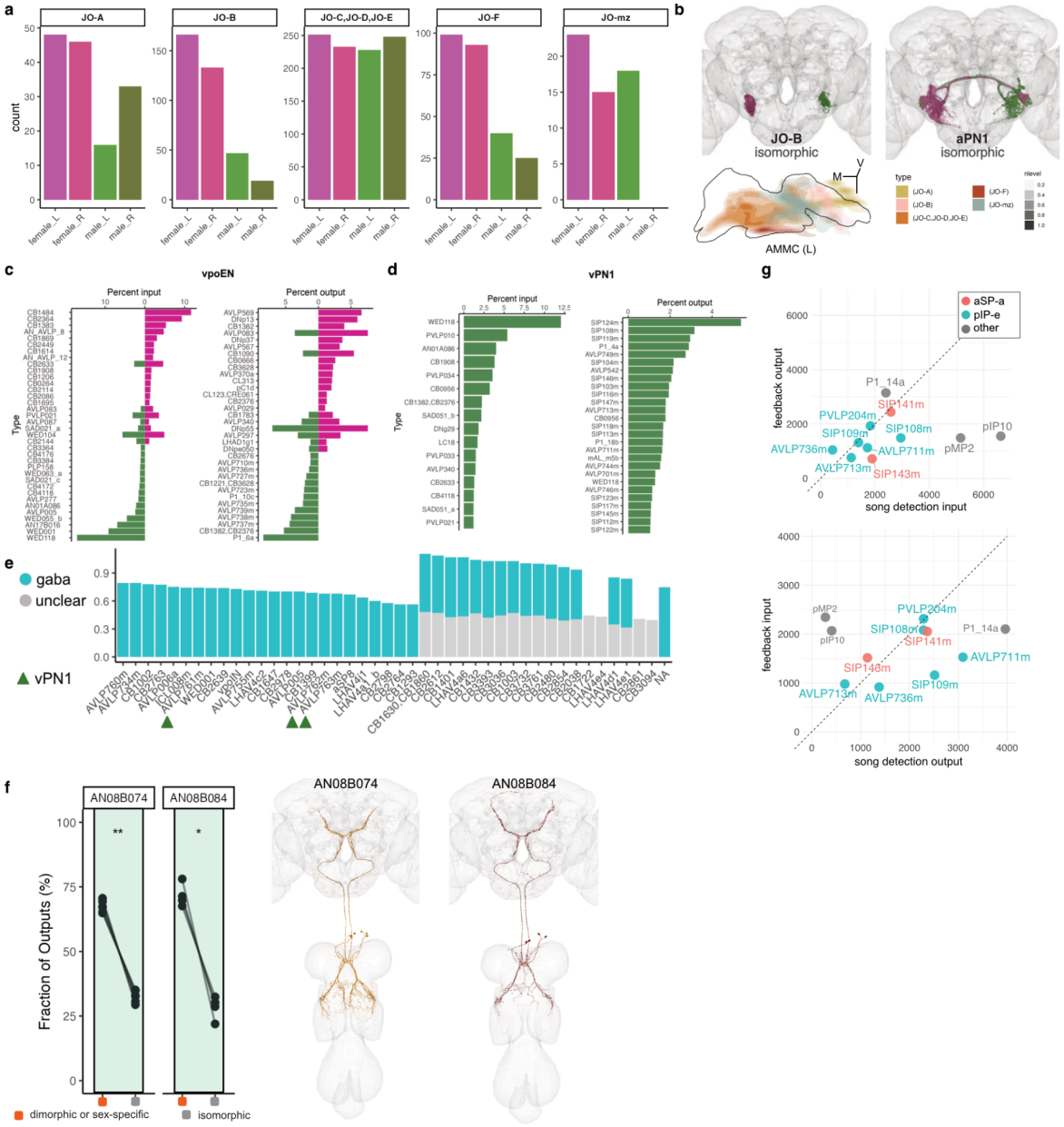
b

neuropil	# cell types		# cells		# input conn		# output conn	
	R	L	R	L	R	L	R	L
LA	15	22	6.9K	4.5K	395.1K	272.9K	529.7K	295.3K
ME	345	366	41.9K	41.8K	15.5M	13.3M	26.7M	27.0M
LO	422	430	25.9K	25.9K	7.4M	6.1M	14.1M	14.4M
LOP	128	125	13.1K	12.7K	3.7M	3.0M	6.0M	5.8M
AME	60	25	137	83	26.8K	7.2K	46.9K	15.1K



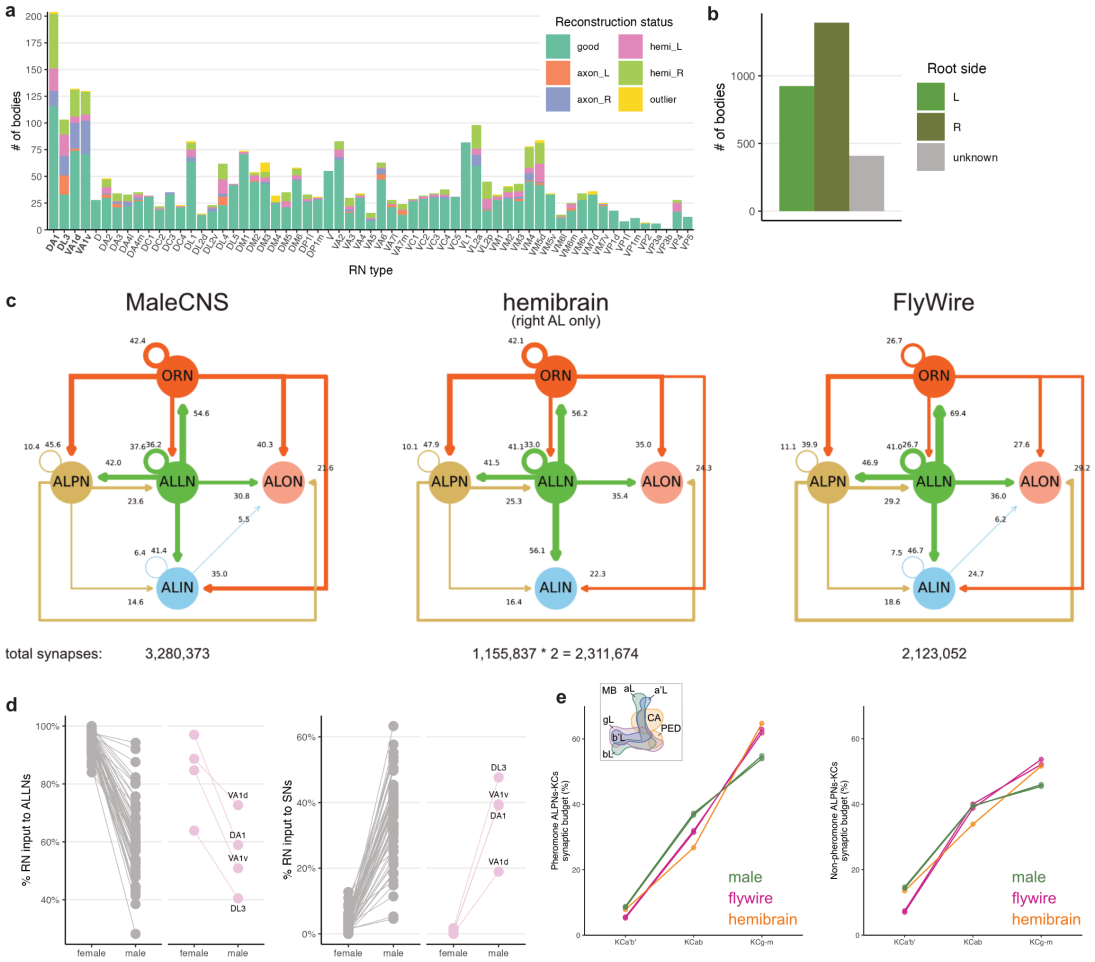
Extended Data Figure 4B | Complete inventory of optic lobe cell types across both brain hemispheres of the male CNS data set, related to figure 4

a Comparative summary of cell type groups showing numbers of cell types, cells, input and output connections across both optic lobes (Cell type groups follow Nern *et al.* 2025, with intrinsic neurons of the optic lobe, referred to as OLIN in Fig 4b, divided into ONIN and ONCN, Optic Neuropil Intrinsic and Connecting Neuron groups.). The table omits cell types not classified as ONIN, ONCN, VPN or VCN (the 'other' group in Nern *et al.* (2025), see Methods). Of the 701 cell types present in both hemispheres, 4 are only found on the right side, and 1 is only found on the left side. **b** The distribution of cells, cell types and connections across the optic lobe neuropils (LA: lamina; ME: medulla; LO: lobula; LOP: lobula plate; AME: accessory medulla). Some differences between left and right hemispheres appear to be due to differences in the position of neuropil boundaries between the two sides. **c** Column ROIs were updated in the right optic lobe, and developed for the left optic lobe, following the methods of Nern *et al.* (2025). This image shows a frontal view of the brain, highlighting the 'patchwork' of column ROIs across the main optic lobe neuropils. The table shows the number of column ROIs in the three columnar optic lobe neuropils. Bilateral layer ROIs are also implemented in the neuPrint database to facilitate analysis (not shown). **d** Scatter plot comparing cell counts per type between left and right optic lobes. Nearly all cell types lie near the unity line, indicating similar numbers of cells / type in both hemispheres. **e** Scatter plot comparing the number of connections per connection type (i.e. ordered pair of connected cell types), quantified as the percentage of connections relative to the total input connections of the postsynaptic type, in the left and right optic lobe. The histogram (blue), aligned with the plot, shows the distribution of ratios of left and right optic lobe input percentages. For cell types with synapses in both optic lobes, the left and right hemisphere cells were treated as different types. Connections show strong approximate bilateral symmetry across the diversity of synaptic connections between optic lobe types. The weights of the indicated connections are very similar between the two male optic lobes but differ in female flies (see Fig 4). **f** Rendering of the aMe12 neurons, whose fine arbors were systematically proofread to provide an improved anatomical marker for typing columns into pale/yellow (Kind *et al.* 2021; Nern *et al. 2025*). The number of aMe12 cells differs between the two hemispheres but the number of vertical branches (see next panel) is similar. **g** Examples of anatomical features used to type medulla columns – generally, columns with an ascending aMe12 branch (right) are typed as pale and those with a Tm5a branch (left) are typed as yellow. Columns with neither aMe12 nor Tm5a branches are also considered probable yellow columns (see below and Methods). When available, R7 photoreceptor connectivity in the column was also considered and some columns with conflicting features classified as unclear. **h** Scatter plot of R7 connections (combined for the left and right optic lobe) to the indicated neurons, with the color coding indicating the presence of Tm5a, aMe12, neither or both, by column. The scatter plot only includes columns with reconstructed R7 photoreceptors, the table inset shows counts for all columns (except in the DRA and at the medulla edge). **i** Scatter plot of R7 connections as in (h) with color-coding now indicating the different column types. Numbers included in the legend are counts for all columns (except DRA and edge). The general approach of classifying columns as pale and yellow followed Nern *et al.* (2025) but the now much more complete aMe12 reconstructions enabled a more complete typing of pale columns. Because we now expect most pale columns to be identified through aMe12 branches, we tentatively assign most of the remaining columns as yellow (yellow (-Tm5), see Methods.) **j** Medulla column maps showing left and right optic lobe column patterns with 6 column identities indicated: pale, two types of yellow columns (generally identified by the presence or absence of a vertical Tm5a branch), DRA (dorsal rim), edge columns which lack R7/R8s, and the few remaining columns indicated as 'unclear.'



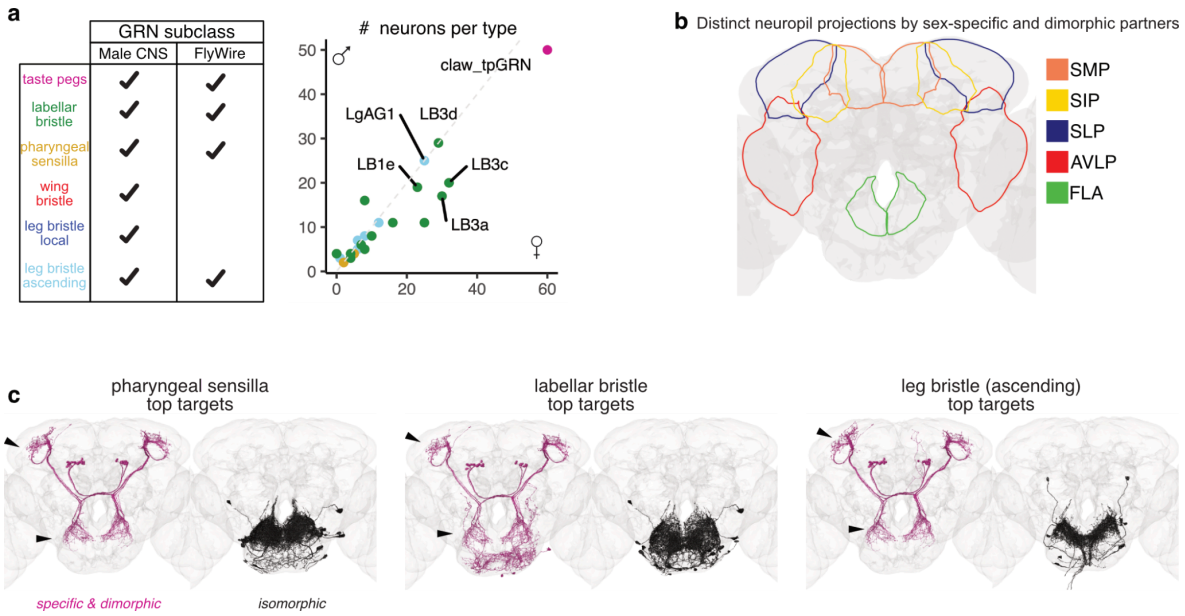
Extended Data Figure 5 | Additional auditory system analysis, related to figure 5

a Johnston's Organ Neuron count by type in males (male CNS) and females (FAFB/FlyWire). **b** Top left: JO-B neurons in female (FAFB/FlyWire, magenta) and male (male CNS, green) brains. Bottom left: Kernel distribution plots of AMMC innervation by JO neuron types in male CNS. Right: Second-order auditory neurons, aPN1. **c** Top input (left) and output (right) partners of vpoEN in males (green) and females (magenta). **d** Same as in c for the male-specific vPN1 neurons (AVLP761m, AVLP762m, AVLP763m). **e** Average confidence score for consensus neurotransmitter predictions in the LHl1 lineage in male CNS; vPN1 cell types indicated by green arrowheads. **f** Left: Fraction of dimorphic and sex-specific (orange) versus isomorphic (gray) outputs for AN08B074 and AN08B084. Each dot is one neuron and paired points are linked. Means were compared using Wilcoxon two-sample tests: ns: p>0.05; ****p≤0.0001; ***p≤0.001 ; **p≤0.01; *p≤0.05. Right: AN08B074 and AN08B084 in male CNS EM space. **g** Scatter plot of the synaptic connection strength with song detection (x-axis) and AN feedback (y-axis) for cell types comprising *fruitless*-expressing clones in the circuit diagrams in Fig 5b, f.



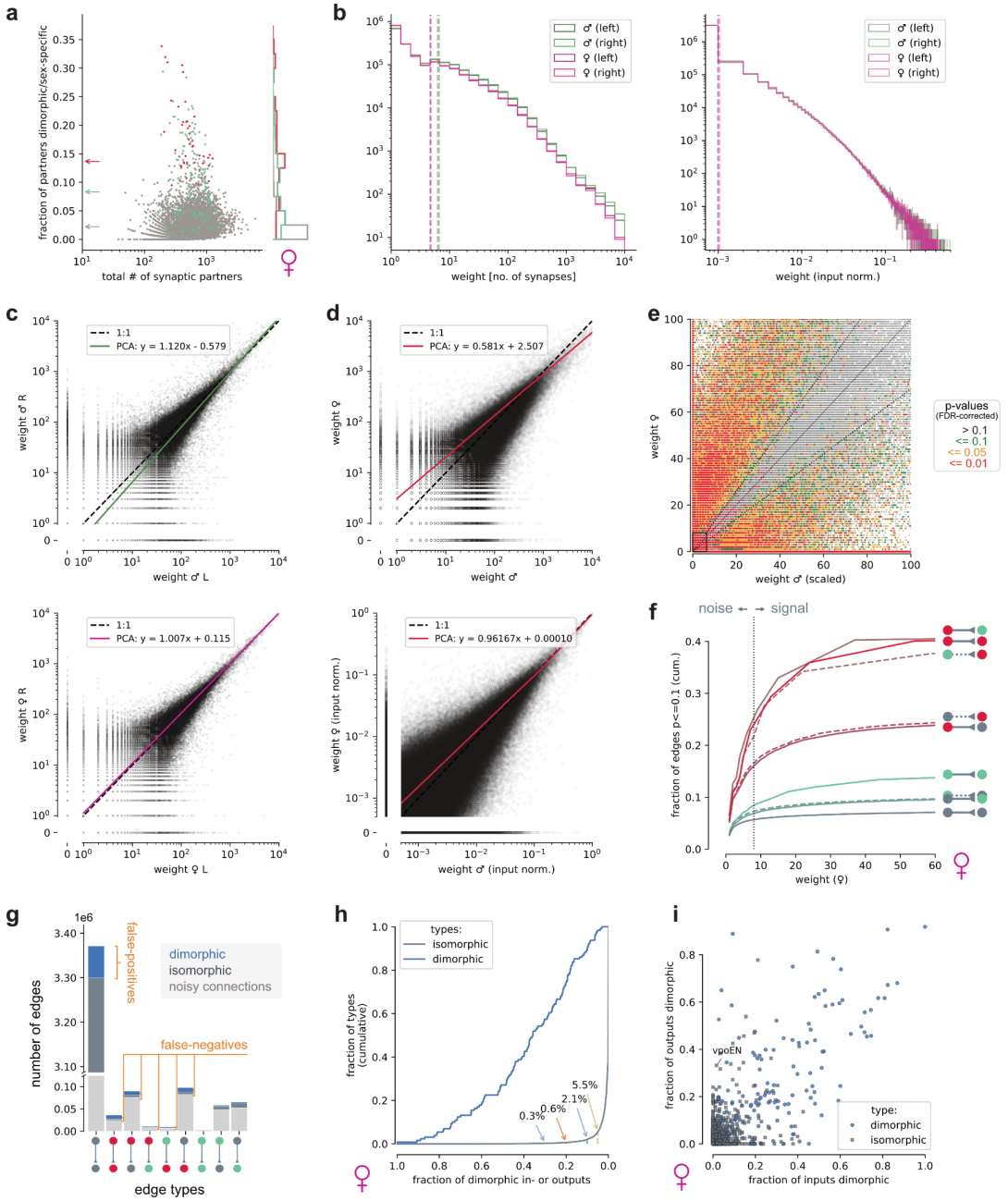
Extended Data Figure 6 | Proofreading and connectivity analysis in the olfactory system, related to figure 6

a Number of bodies per RN type and its reconstruction status. axon_L/R: axon (presynapses) only present on that side, though the body crosses the midline. hemi_R/L: body ends around the midline, and only exists on one side. Outlier: cases in which a body innervates more than one glomerulus on one side or does not arborise a glomerulus proper. **b** Number of bodies per RN type and per root side. **c** Input-normalized wiring diagram between AL cell classes for AL-intrinsic connectivity in males (left) and females (FAFB/FlyWire, right). **d** Comparison of the percentage input to RNs from ALLNs (left) and sensory neurons (right), for the female (FAFB/FlyWire) and male brains. ALLNs and sensory neurons are the top 2 classes that input to RNs. **e** Comparison of the synaptic budget, as percentage for the connections from ALPNs for the main types of Kenyon cells in the male and females brains; Left: for pheromone ALPNs; Right: for non-pheromone ALPNs. Data for each side is shown separately for FAFB/FlyWire and the male CNS brain.



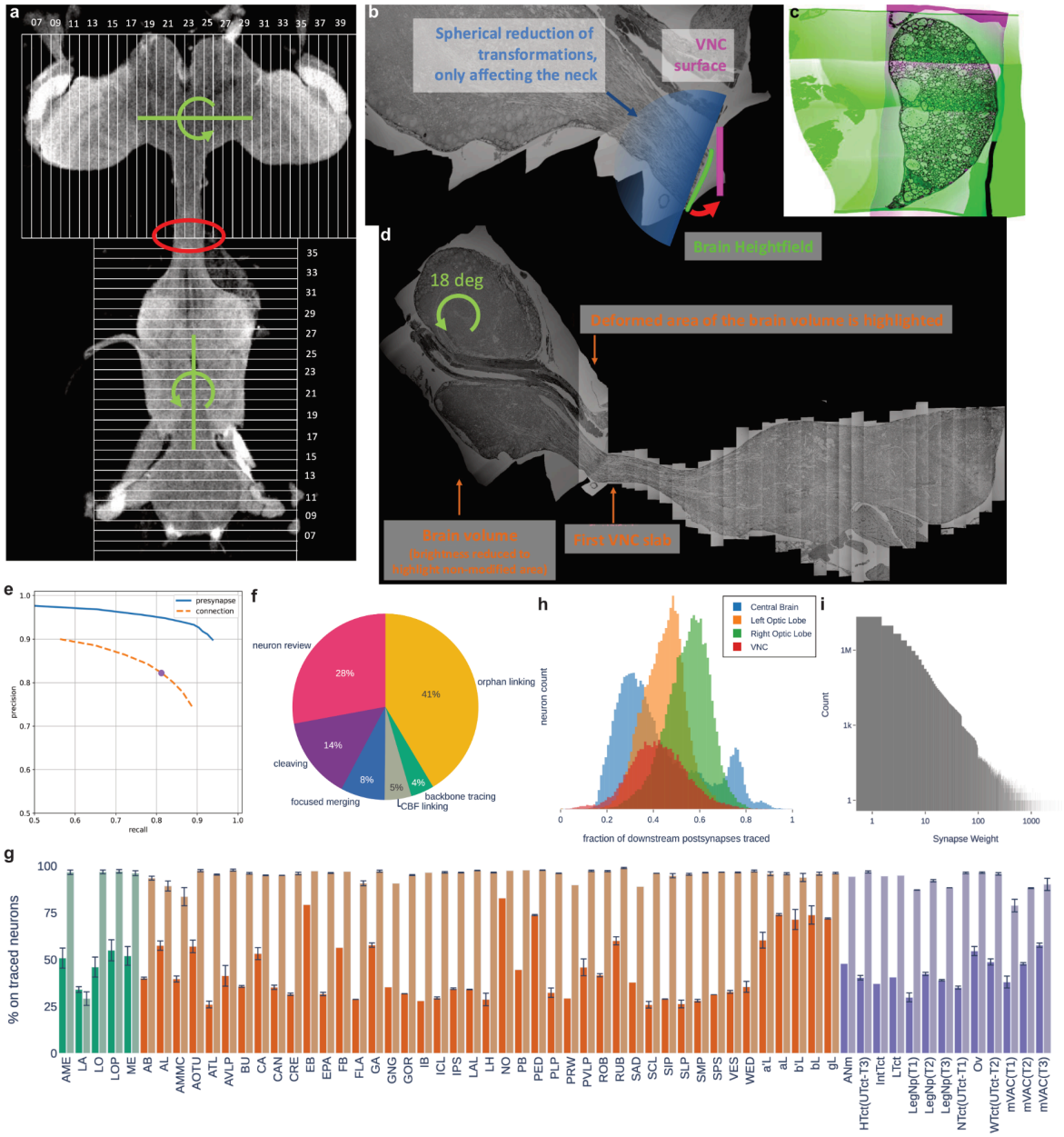
Extended Data Figure 7 | Additional gustatory system analysis, related to figure 7

a Left: Table representing taste sensory classes present in male CNS versus FAFB/FlyWire data. Wing bristles and local leg bristles are exclusive to the VNC. Right: Comparison of GRN cell type counts across males and females (pink: taste pegs; green: labellar bristles; yellow: pharyngeal sensilla; red: wing bristle; navy: local leg bristles; cyan: ascending leg bristles). **b** Strongest neuropils innervated by second-order sex-specific and sexually dimorphic gustatory neurons. **c** Top ten targets downstream of GRN types in female (FAFB/FlyWire), by type.



Extended Data Figure 8 | Supporting dimorphism analyses, related to figure 8

a Dimorphic up- and downstream synaptic partners as a fraction of total synaptic partners for all cross-matched female cell types. Arrows on the y-axis indicate means for iso-, dimorphic and male-specific types. **b** Histogram of total (left) and input-normalised (right) cross-matched type-to-type edge weights for both male and female. Dotted vertical lines indicate the means. **c** Left vs right weights for cross-matched type-to-type edges in male (top) and female (bottom). Green/magenta line represents PCA fit. **d** Male vs female edge weights for cross-matched types. Top: total number of synapses; bottom: input normalised. Red lines represent PCA fit. **e** Zoom-in on the lower-left portion of Fig 8d. Black rectangle indicates area of noisy connections: ≤10 and ≤8 synapses in male and female, respectively. **f** Cumulative fraction of female edges with FDR-corrected p-values below 0.1 per edge type. Dotted vertical line marks 90% probability threshold from Fig 8e. **g** Total number of dimorphic, isomorphic and noisy connections (male + female) broken down by edge type. **h** Fraction of iso- and dimorphic types with at least X% dimorphic in- or outputs (by synapse count) in female. **i** Fraction of dimorphic in- versus outputs (by synapse count) per cell type in the female.



Extended Data Figure 9 | Dataset alignment and proofreading metrics, related to figure 1 and Methods

a Overview of the entire CNS and the slicing into slabs for FIB-SEM imaging. The red ellipse highlights the brain/VNC cut, green rotation axes show the degrees of freedom wrt to slab orientation. **b** Transformations that were applied to the brain and VNC volumes to stitch them seamlessly. **c** Overlay of the extracted surfaces of the brain (green) and VNC (magenta). Note the 4 slabs that are visible in the brain surface. **d** Cut through the entire CNS volume highlighting the connection between brain and CNS, the modified area of the brain for stitching both volumes, and the slabs of the VNC. **e** The precision-recall curves for presynapses and connections, sweeping across the model's output confidence score. Our published synapses are filtered with a confidence threshold of 0.5 (purple dot), resulting in overall precision of 0.82 and recall of 0.81. **f** Estimated proportion of proofreading labor spent in each major proofreading protocol. **g** Traced completeness of synapses across neuropils. Light bars show presynapse completeness, dark bars show postsynapse completeness, and hue differentiates between optic lobe, central brain, and VNC neuropils. For paired left and right neuropils, the whiskers indicate the spread between left and right

values and the bar shows the mean. **h** The distributions of downstream capture fraction for traced neurons in the central brain, optic lobes, and ventral nerve cord. **i** The distribution of synaptic partner counts of remaining unmerged 'orphan' fragments.

Methods

A static download of the male CNS raw data is available in the google bucket gs://flyem-male-cns. A landing page with ways to interactively explore the data can be found at https://male-cns.janelia.org/. Updated annotations for FlyWire are available at https://github.com/flyconnectome.

EM Sample Preparation

Methods for sample preparation were described in detail in Nern *et al.*[36], an earlier study of the same sample. Briefly, hundreds of five-day-old *Drosophila melanogaster* males from a cross between Canon S strain G1 × w^{1118} were dissected to extract the CNS intact, including the brain, VNC and neck connective. After a multi-stage fixation and staining process, each was inspected for significant damage, with special attention to the fragile neck connective. After initial inspection, 44 were examined in detail via X-ray CT imaging to check for more subtle flaws and to assess the staining. The sample identified internally as 'Z0720-07m' was selected as having the best quality.

Hot-knife cutting

As the *Drosophila* CNS is too large to image by FIB-SEM as a contiguous block, we cut it into 20 µm-thick slabs via our "hot-knife" sectioning procedure [166] (Extended Data Fig 9a). The VNC was sectioned first into a total of 31 slabs using cuts along transverse planes. The brain was then sectioned into 35 slabs with sagittal cuts (orthogonal to those in the VNC). Quality of each slab was assessed by LM, followed by mounting, laser-trimming, and further inspection by X-ray CT.

EM Volume Imaging

As explained in Nern *et al.*[36], we followed the imaging methods first described in Takemura *et al.* [34] with minimal modifications. We employed a fleet of seven customized FIB-SEM machines to separately image each of the 66 hot-knife slabs over the course of a year. SEM images were acquired at isotropic 8nm in-plane resolution at 3 MHz using a 3 nA beam with 1.2 kV landing energy. FIB milling was performed with a nominal 8 nm step size using a 15 nA 30 kV Ga ion beam.

EM Volume Alignment

As the brain and VNC volumes of our sample were imaged and hot-knife sectioned separately, we first assembled and stitched the hot-knife slabs of each volume independently, following the methods described in Nern *et al.*[36].

Following a single cut through the neck that separated the sample into brain and VNC, the hot-knife sectioning of the brain and the VNC were performed orthogonally to each other (Extended Data Fig 9a). Hot-knife sectioning fixes the two in-plane imaging axes, leaving the rotation around the milling axis as a free variable.

For convenient viewing and analysis, we chose to orient the brain volume such that all three of its anatomical axes approximately coincide with the volume coordinate axes. The faces of each hot-knife slab are sagittal sections, with the sagittal axis coinciding with the X axis of our aligned volume. We rotated the brain around the sagittal axis, tilting the head back by 18 degrees to align its dorsal-ventral axis with the Y axis of the volume and its anterior-posterior axis with the Z axis. In the VNC, the hot-knife cuts are transverse sections, with the Z axis reasonably aligned to the sample's anterior-posterior axis.

We then proceeded to stitch together the brain and VNC volumes at their interface in the neck connective (Extended Data Fig 9b-d). The cut through the neck spanned four hot-knife brain slabs of the brain volume on the anterior side, whereas it formed the first slab surface of the VNC volume on the posterior side. To extract the cut surface in the brain volume, we adjusted our hot-knife surface finding code and mostly relied on the BigDataViewer-based interactive tool to manually define the heightfield describing the exact location of the surface in the brain volume. An angle difference of ~25 degrees remained between the surfaces. To match both volumes seamlessly, we developed code that applied a single non-rigid transformation consisting of the surface deformation field, the surface heightfield (including the ~25 degree rotation), and a global translation. The software reduces the magnitude of the transformation as a function of distance from the stitching plane to ensure a smooth transition that is limited to the neck region, since proofreading had already started in the brain volume. After interactively confirming the correctness of this complex transformation on the two large VNC and brain volumes in BigDataViewer, we joined both volumes into a single, seamless volume of the entire CNS.

EM Volume Segmentation

Segmentation for neurons and semantic masks (nuclei, glia, etc.) was performed with the same methods as the MANC VNC volume[34], with some differences for this sample as described in Nern *et al.*[36]. Because the complete CNS volume was imaged and aligned as three separate subvolumes to be stitched together (right hemisphere, left hemisphere, and nerve cord), the segmentation procedure was run three times. For the nerve cord portion, a separate semantic segmentation model was trained to properly differentiate between muscle tissue and the nerve cord. Stitching the main segmentation for the left hemisphere onto the right hemisphere (and the VNC onto the brain) required care, as the earlier portion had already undergone significant manual proofreading by then. The segmentation region for each subsequent subvolume was constructed to overlap with that of the preceding subvolume. In the unified agglomeration, merges across the stitching boundary were selected according to the highest count of shared voxels among agglomerated segments within the overlapping region. Separation constraints to forbid merges between nuclei and fibers in the same nerve bundle (or the cervical fiber bundle) helped to avoid introducing false merges in already proofread segments.

EM Volume Synapse Identification

We performed synapse prediction by extending the methods as described in the optic lobe reconstruction [36]. Networks for presynaptic T-bar detection and postsynaptic partner detection from that reconstruction were further fine-tuned with additional training ground-truth synapse data collected in the brain and VNC regions of the full CNS sample.

As with the previous reconstruction, we collected separate validation ground-truth to assess the performance of the synapse identification. In total, synapses were densely labeled in 114 cubes of 300 × 300 × 300 voxels, spanning 81 ROIs. Cube locations were selected to cover distinct ROIs, and randomly selected within a given ROI. Altogether, the subvolumes contained 2,303 annotated T-bars and 16,870 annotated postsynaptic partners.

By selecting validation cubes that span many ROIs, we sought to better assess global synapse prediction accuracy, as well as identify any potential problematic ROIs. In our case, initially selected validation cubes in the lamina (LA) showed poor recall in the set of synapse predictions. This recall issue resulted from some presynapses in the lamina having a differing morphology, which was not well-represented in the original training set. We subsequently used these annotated lamina cubes to fine-tune a new T-bar detector, which we applied to the lamina ROIs, adding any predictions made by the new detector that did not already exist in our original set. (New validation cubes were then sampled and annotated for the lamina.)

Extended Data Fig 9e gives the overall precision-recall plots for T-bars alone and synapses as units (both components correctly predicted); performance is comparable to the optic lobe subset. Extended Data Fig 1i gives the precision/recall for each ROI, for T-bars alone, and for synapses. Circle area is proportional to ROI volume, and color indicates ROI location, with red used for brain ROIs and blue for VNC ROIs. There is some variation in accuracy across ROIs, but performance is largely clustered, and generally above 0.8 recall for T-bars alone and 0.7 recall for synapses.

Neurotransmitter prediction

Ground Truth

The ground truth for neurotransmitter prediction is made up of data from the literature, as well as experiments run at Janelia, and is available as a regularly updated resource on Github. This resource maps cell types to the emission of ten neurotransmitters: acetylcholine, dopamine, GABA, glutamate, glycine, histamine, nitric oxide, octopamine, serotonin, tyramine. The data is kept in ternary form for each neurotransmitter, a value of `-1` signifying an absence, a value of `+1` signifying a presence, and a value of `0` signifying that the neurotransmitter was not tested for. The specific subset of cell types used to train our model can be found in the gt_sources directory of that repo.

The cell types from the resource were matched to MaleCNS cell types according to the `flywireType` and `mancType` neuprint columns, taking synonyms into account from FAFB/FlyWire. We then filtered the ground truth to exclude entries with an evidence confidence rating below 3, removed instances of co-transmission (multiple `+1` values when

pooled across studies of the same cell type) and dropped any cell types for which positive and negative evidence exists for the same neurotransmitter. Disjoint training and validation datasets of cells were created (80% and 20% of the neurons, respectively), stratified so that they held a similar distribution of neurons from each class. The automatically detected T-bar locations for each cell were listed, and we verified that the split (80/20) was still valid at the synapse-level.

Model training

We trained an image classifier network following Eckstein *et al.*[39] to predict neurotransmitter identity of a pre-synapse from a region of interest centered around a T-Bar, and spanning $640nm^3$. The network outputs a normalized score for each of the 7 neurotransmitters considered: the scores add up to 1, and are akin to a probability. The highest number is chosen as the predicted neurotransmitter.

The classifier network is a ResNet50[167] model. It was trained using stochastic gradient descent on 100,000 mini-batches of 32 volumes each. All input volumes were intensity-normalized to the range [−1,1]. The data was randomly augmented during training with random axis flipping; affine transformations with rotations up to ±π radians, shear up to ±0.1, translations up to ±10 voxels, and scaling within ±10%; intensity scaling by ±20% with fixed mean; intensity shifts up to ±0.2; Gaussian noise with mean 0 and standard deviation 0.1; and Gaussian smoothing with sigmas randomly sampled between 0.1 and 0.5 along each spatial axis. We used the **`AdamW`** optimizer with a learning rate of 1×10^{-4} and parameters $\beta=(0.9,0.999)$, $\lambda=0.01$, where β corresponds to the momentum parameters and λ to the rate of weight decay. Code for training and inference is available on Github.

Assignment of neurotransmitter predictions to neurons

Each segment was assigned an aggregate neurotransmitter prediction according to the scheme described in Nern *et al.*[36]. Accompanying the predictions we provide a confidence score for each segment's assigned prediction according to the formula in Eckstein *et al.* [39] (Extended Data Fig 1k). Each presynapse in a segment is assigned a confusion score by selecting an entry from the synapse-level confusion matrix: the row is determined by the owning segment's overall prediction and the column determined by the presynapse's model prediction. The segment confidence score is defined as the mean of its presynapse confusion scores.

The database records the most frequent prediction among a neuron's presynapses in the `predictedNt` property, except for those marked `unclear` as noted below. The most frequent presynapse prediction when pooled across all cells of a common type is recorded in `celltypePredictedNt`, except for those marked `unclear`. The confidence score accompanying `predictedNt` is given in `predictedNtConfidence`, and the confidence accompanying `celltypePredictedNt` is given in `celltypePredictedNtConfidence`.

Neurons or fragments with fewer than 50 presynaptic sites or those whose `predictedNtConfidence` is below 0.5 are given `predictedNt` of `unclear`. Similarly, cell types with fewer than 100 presynapses when pooled across all corresponding neurons or cell types whose `celltypePredictedNtConfidence` is below 0.5 are given a `celltypePredictedNt` of `unclear`.

Finally, the `consensusNt` property is a copy of `celltypePredictedNt`, except in cases where experimental ground truth for the cell type is available to override the model prediction. Additionally, all octopamine and serotonin results are set to unclear in `consensusNt`, owing to the relatively scant validation data used for those neurotransmitters. The `consensusNt` is the recommended property to use in most analyses.

EM Volume Proofreading

Major phases of proofreading

Current state-of-the-art automated neuropil segmentation methods leave many unresolved errors requiring manual proofreading to identify and correct. We executed a combination of bottom-up and top-down proofreading protocols using a software toolchain for connectomic reconstruction including NeuTu[168], Neu3[169], and DVID[170] (Extended Data Fig 9f). Further descriptions and rationale are provided in Nern *et al.*[36]. As the image volume was assembled in three major phases (right hemisphere, left hemisphere, and nerve cord), we repeated all major protocols in our proofreading process for each subvolume as it became available.

The first phase was cell-body fiber linking, in which we attached orphaned cell bodies (somata) to their main axons. Next, we followed our cleaving protocol in order to eliminate major false merges in all segments deemed significant according to their synaptic counts or other qualities, such as passing through the cervical fiber bundle.

With the dataset largely free of major false merges, we could begin efficiently assembling fragments together into recognizable cell shapes. In the backbone tracing protocol, we targeted synapse-rich segments for coarse tracing until no obvious false splits remained on large branches.

To increase the fraction of synapses captured by our traced backbones, we executed two bottom-up protocols aimed at connecting medium or small fragments to their target neurons. The focused merging protocol provided automatically selected merge proposals for directly adjacent segments to a proofreader as a binary decision. The orphan linking protocol tasked proofreaders with tracing a fragment to a backbone segment (without knowing which target it is destined for). We attempted to trace every fragment with 100 or more synaptic connections throughout the dataset. In the central brain and right optic lobe we went further, examining fragments with at least 50 synaptic connections.

The final phase of proofreading is purely top-down: neurons are assessed holistically to spot overlooked false merges or false splits. In this reconstruction of an entire CNS, we often had the benefit of examining pairs or groups of homologous neurons in tandem to spot gross inconsistencies between cells of the same type. This protocol was executed primarily by proofreaders in the central brain and right optic lobe, whereas we relied on the cell typing process to flag errors in the left optic lobe and VNC.

In addition to our major proofreading protocols, expert neuroanatomists from both Cambridge and Janelia examined all neurons as they typed and annotated them, providing a final quality check as poorly reconstructed neurons cannot be easily clustered and typed.

Our proofreading team is staffed almost entirely by annotators with experience from earlier connectomic reconstructions. Newly hired proofreaders received at least six weeks of training using a separate database before transitioning to the production environment. Regular “refresher” training was given to all proofreaders when we transitioned between major phases of proofreading. Two senior proofreaders took on a specialized role to provide oversight and quality control, reviewing the work of other proofreaders in addition to performing their own proofreading tasks. Based on an analysis of our edit logs and task management records, we estimate that our proofreading team spent approximately 44 person-years on the CNS dataset.

AutoProof

As described in the section ‘Major phases of proofreading’, significant effort is spent manually proofreading the automated segmentation, and this process constitutes the most labor intensive component in generating a connectome reconstruction. With the accuracy of current automated segmentation methods, proofreading the entire segmentation is intractable. Manual effort is instead spent to target a specific connectivity coverage (see section Major phases of proofreading). This workflow leaves a certain amount of the segmentation unexamined; within the orphan linking protocol, disconnected orphan fragments are only examined if they are above a threshold for synaptic weight.

We developed a new procedure, AutoProof, to automatically process these unexamined fragments and select a subset that can be joined to target neurons with high confidence. A machine learning model is first trained on the manual proofreading decisions from the focused merge protocol, thereby learning, given a pair of adjacent segments, whether the segments belong to the same body or not. This model is then applied to all unexamined orphan fragments in the central brain and nerve cord with a synaptic weight of ten or higher. The full details of Autoproof are given in [171].

A random sample of orphan-to-target merges proposed by AutoProof was manually verified, and used to select a high conservative threshold, targeting a low estimated error rate of ~3%. All proposed merges above this threshold were automatically accepted without explicit human verification; the risk is in part mitigated as any given orphan is of small synaptic weight and therefore individual errors would have minimal impact on the overall connectivity.

For the male CNS reconstruction, AutoProof helped the completion rate significantly. About 200 thousand orphan link proposals were automatically accepted, adding about 2.4 million PSDs and 309 thousand T-bars. These synapses added about 1.3% to the connectivity completion rate. At an estimated 200 tasks per day for a human annotator working in the orphan link protocol, this automated procedure was equivalent to about 4 person-years of work.

Quality metrics

Quality of a connectome can be assessed using a variety of metrics. One important metric is the overall fractions of presynapses and postsynapses which have been captured by 'traced' neurons, known as presynaptic and postsynaptic 'completeness'. As can be seen in Extended Data Fig 9g, presynaptic completeness tends to be much higher than postsynaptic completeness, as presynapses typically reside on larger-calibre neurites which are more easily merged via both automated segmentation and manual proofreading. This trend is also observed in prior large-scale *Drosophila* connectomes [30,32,34].

A synaptic connection is only useful to downstream analyses if both its presynapse and postsynapse belong to traced neurons, so a more informative metric is the connection completeness, i.e. the fraction of synaptic pre-to-post connections in which the neurons on both sides have been traced. Fig 1d shows the fraction of completed connections in each neuropil, with an overall average of 40.1%. Empirically, connection completeness is approximately equivalent to the product of presynaptic completeness and postsynaptic completeness.

However, not all neurons in a compartment are equally well traced. An informative neuron-centric metric is the 'downstream capture' of each neuron, which is defined as the fraction of synaptic outputs which connect to traced neurons. Even when a neuron is itself completely reconstructed, if its postsynaptic partners are poorly reconstructed then its connectivity to downstream neurons will be poorly characterized. The discrepancy between compartment-level completeness and neuron-level connection recall is revealed by the downstream capture metric. The distribution of downstream capture fractions among neurons in the major compartments of the CNS is shown in Extended Data Fig 9h.

It is worth noting that the downstream capture distribution for the central brain is bimodal. The second peak is chiefly due to populations of neurons whose outputs are in areas with relatively high postsynaptic completeness: the EB, FB, and NO in the central complex; the antennal lobes; and all compartments of the mushroom bodies.

Another quality metric is the number of unmerged 'orphan' fragments in the dataset and their distribution of synapse counts. The largest of such orphans remain unmerged in our dataset due to data artifacts or especially complex morphologies which make it difficult or impossible to find the site at which they should be traced to a neuron. We inspected and attempted to eliminate all orphan fragments with 100 or more synaptic partners. There are 5,329 remaining orphan fragments at or above that threshold in the proofread dataset. In total, there are 84.6 million orphan fragments in the dataset, most of which contain very few synapses. The final distribution is shown in Extended Data Fig 9i.

Spatial Transforms

We generated spatial transforms to register the Male CNS to other coordinate spaces, including the JRC2018M brain light microscopy template[75] (procedure described in Nern *et al.*[36]), and the MANC, FAFB/FlyWire and hemibrain connectome datasets. In all cases, we began with an automated registration between synapse point clouds using either Elastix[172] or CMTK (RRID:SCR_002234) to produce a non-linear transform. Where necessary, we fine-tuned the transform using BigWarp[173] in ImageJ/Fiji by manually adjusting pairs of

corresponding landmarks. In addition to these bridging transforms, we also generated a transform to mirror the MaleCNS across the midline which aligns homologous neurons from the left hemisphere to the right or *vice versa*. All transforms are accessible with *navis-flybrains* (see Table 2) and can be chained with existing transforms to map to additional coordinate spaces, such as JRC2018 unisex brain, the JRC2018 unisex VNC, etc using *navis*.

Defining anatomical regions in the EM volume

As described in Nern *et al.*[36], the primary neuropil regions were initialized via transfer from the JRC2018M template[75] using the synapse point cloud to register the volume. We then refined the boundaries of those regions which did not align cleanly to the underlying EM data or relevant populations of segmented neurons.

Analysis Software

Data curation and analysis was carried out with a combination of free and open source software tools for R and Python, principally from the *natverse* (https://natverse.org/) and *navis* (https://navis-org.github.io/navis/) ecosystems developed in Cambridge.

Table 2: Software products used for analysis

Name	Github repository	Description	Citation
malecns	flyconnectome/malecns	Support for working with male CNS segmentation, meshes and annotations in R	this study
coconatfly	natverse/coconatfly	Analysis suite of comparative connectomics in R	Schlegel *et al.*, Nature (2024)
fafbseg	natverse/fafbseg	Support for working with FAFB/FlyWire segmentation, meshes and annotations in R	Bates *et al.*, eLife (2020)
malevnc	natverse/malevnc	Support for working with MANC segmentation, meshes and annotations in R	Bates *et al.*, eLife (2020)
neuprintr	natverse/neuprintr	Support for working with neuPrint databases	Bates *et al.*, eLife (2020)
neuprint-python	connectome-neuprint/ neuprint-python	Python API for working with neuPrint databases	[174]
bigclust	flyconnectome/bigclust	Set of GUI tools for inspecting neuron clusterings and assigning annotations	this study
cocoa	flyconnectome/cocoa	Python tools for connectivity co-clustering	Schlegel *et al.*, Nature (2024)
NBLAST scoring matrices	flyconnectome/nblast-scoremats	Scoring matrices for NBLAST generated from cross-matched neurons	this study

fafbseg-py	navis-org/fafbseg	Support for working with FAFB/FlyWire segmentation, neuron meshes/skeletons and annotations in Python	Schlegel *et al.,* Nature (2024)
flybrains	navis-org/navis-flybrains	Python package bundling spatial transform between various template spaces, including to/from the male CNS. Used in combination with `navis`.	

Annotations

Each neuron in the dataset was given a set of annotations for various anatomical, developmental and descriptive features. We highlight some of the main ones below.

Superclass

Superclasses describe broad sets of neurons, grouped together by anatomy or general function. Bodies in the dataset are defined as neurons if they have a superclass. Bodies without one are fragments of neurons. We define 20 superclasses: intrinsic neurons are those contained entirely within the optic lobes, central brain or VNC; visual projection neurons connect the optic lobes and the central brain while visual centrifugal neurons do the opposite; sensory neurons extend their axons from the periphery into the CNS; sensory ascending or sensory descending neurons are sensory neurons that extend from the VNC into the brain or from the brain to the VNC, respectively; ascending neurons have their somas in the VNC and extend into the brain while descending neurons do the opposite;. motor neurons extend their axons out of the CNS to connect to muscle; efferent neurons are non-motor efferent that can be found entirely contained in the central brain or VNC or connecting these 2 regions (descending or ascending); finally endocrine neurons connect the central brain to the corpora allata or cardiaca endocrine glands.

Superclasses that are found across the CNS such as intrinsic and sensory, are given a prefix to distinguish between the populations in the optic lobe (ol-), central brain (cb-) and VNC (vnc-).

Hemilineage

Hemilineage annotations were transferred from the FAFB/FlyWire[30,31], hemibrain[32], and MANC[33,34] datasets according to cross-matched neuron types. Unmatched types and many:1 matches were reviewed as described in Schlegel *et al.*[31].

Supertype

Supertypes were assigned on a per hemilineage basis to morphologically similar neurons in the central brain using morphological (NBLAST) clustering[31,40] and subsequent visual inspection. Neurons were grouped into a supertype if their main arbours aligned and when dendrites and axons were mostly overlapping in 3D space.

In some cases, as with the SLPal2 hemilineage, sex-specific terminal cell types can be linked together through their supertype designation. For example, supertype “12551” includes a group of sex-specific neurons previously described as the sexually dimorphic aSP-g[26,60] or aSP6[56] cluster. While these neurons differ widely in morphology and

connectivity, preventing them from being linked at the level of terminal cell types, their classification under a common supertype reflects a shared development underpinning sex-specific functions within their respective neural circuits[20,26,134].

Dimorphism

Dimorphism annotations were added to neurons on a per cell type basis according to a set of operational definitions used to describe three categories (1) sex isomorphic, (2) sexually dimorphic, and (3) sex-specific. Neurons from the FAFB/FlyWire, hemibrain (where possible), and male CNS datasets were clustered based on morphological (NBLAST) and connectivity (cosine similarity) metrics, and visualized with a dendrogram (Ward's method) or a low-dimensional embedding (UMAP) (see also Extended Data Fig 8a-d). Isomorphic neurons were matched across hemispheres and datasets, while sex-specific neurons were defined as having no probable match across opposite-sex datasets despite bilateral consistency within sex. Sexually dimorphic neurons were annotated when neurons could be closely associated enough such that they were clearly arising from the same cell type, but demonstrated numerical and/or morphological differences across sexes despite their shared developmental history. In some developmental lineages (e.g. FLAa3), high morphological similarity between types obscured our type-to-type matches. In many cases, types that fall into this category are considered “sex-specific”, but integration of future datasets may enable stronger type matching and these cells could turn out to instead be sexually dimorphic. Due to the lack of a fully annotated female VNC connectome, our dimorphism annotations are focused on the central brain and optic lobes. While we were able to add some additional dimorphism annotations for ascending neurons with extensive arbours in the brain, the majority of dimorphism annotations in the VNC come from existing literature[49,55].

We offer a basic confidence assessment for our dimorphism annotations: dimorphic neurons are labeled either “sexually dimorphic” or “potentially sexually dimorphic”, and sex-specific neurons are labeled “male-specific” or “potentially male-specific”. We consider types with the qualifier “potentially” as lower-confidence annotations. However, analyses of dimorphism throughout the paper consider all dimorphism labels regardless of their confidence.

fruitless, *doublesex* and synonyms

Neurons in EM data were annotated as putatively expressing *fruitless* and/or *doublesex* according to comparison with light microscopy data transformed and projected into a registered template space[75,175]. The light level image data were obtained from Virtual Fly Brain[176]. Original data were sourced from Cachero *et al.*[60] and Chiang *et al.*[67] for *fruitless,* and Nojima *et al.*[27] for *doublesex*. EM neurons were chosen for inspection against light data based on hemilineage assignment, since each light-level image was generated from individual lineages marked as 'clones'[67,177]. Limitations due to lack of hemilineage assignment, ambiguity in lineage/cell type delineation, and technical limitations imposed by the genetic labeling prevented annotation for certain groups of cells. Specifically MARCM clone data are missing most primary neurons. The optic lobes where most neurons are have a different pattern of neurogenesis have not been well-characterised. Finally we excluded expression in mushroom body Kenyon cells where the subpopulation expressing *fruitless* cannot be clearly delineated.

EM neurons were compared to light images based on overlap in three-dimensional space and scored as 'high', 'low', or 'NA' indicating the amount of overlap with the clone and/or

other evidence of gene expression according to previously published immunohistochemistry or transcriptome data, including Allen *et al.* 2025 [69]. Hemilineages were putatively assigned to clones according to Costa *et al*. 2015 [178]. Annotations were further reviewed to ensure that neurons with the same cell type received the same annotation except in exceptional circumstances.

Previous estimates quantifying *fruitless* expression range from 1,500 to 2,000 total neurons [56,179,180]. These estimates were generated using different methods to detect *fruitless*: the fru-GAL4 genetic driver line identifies approximately 1,500 cells, while FruM antibody stains at least 2,000 cells[139]. Other relative estimates report *fruitless* expression as 0.5% [10] or 2%-3% [56,60,129,154] of the CNS. More recently, estimates from single-cell transcriptomics suggest that 4% of neurons in the central brain express *fruitless,* in line with our high-confidence annotations[69] (Extended Data Fig 2j). Studies estimating the extent of *doublesex* expression in the male central nervous system also vary: immunostaining against DSX estimates 320-432 cells[181], the dsx-GAL4 driver line finds 900 cells[182], MARCM identifies 178 cells[27], and scRNAseq suggests 0.6% of the central brain (corresponding to ~290 cells)[69]. Another study of *fru*- and *dsx*- expressing neurons in FAFB/FlyWire identified 1,357 putative *fruitless*- and 129 *doublesex*-expressing cells[70]. Both that study and the one presented here fall within reason of previous estimates.

The synonyms column was filled for EM neurons which could be matched to previously published literature, especially when one or more names are used to describe the same cells. For putatively *fruitless*- and *doublesex*-expressing neurons, the name of the matching light-level clone [56,60,67] were added to neurons with 'high' and 'low' confidence scores according to manual visual assessment.

Updated FlyWire annotations

In the process of adding annotations to the male CNS, we also added new (`fru_dsx` for *fruitless* and *doublesex* expression; `dimorphism` and `matching_notes` for dimorphic neurons; `supertype` matching the same field in neuPrint) and revised existing annotations for FAFB/FlyWire. The latter mostly affected `cell_type` and `hemibrain_type` but we also made minor adjustments to `super_class`, `ito_lee_hemilineage` and `side`. In an effort to reconcile cell types for optic lobe-intrinsic neurons, we also integrated the cell types from Matsliah *et al.* [74] with our original annotations. The `flywireType` field in neuPrint corresponds to these updated annotations (either `cell_type` or `hemibrain_type`) which have been deposited at https://github.com/flyconnectome/flywire_annotations.

Typing and cross matching

Typing in the central brain and the ventral nerve cord

Neurons were principally typed by cross-matching to the FAFB/FlyWire[30,31,74], the hemibrain[32] and the male adult nerve cord (MANC)[33,34]. The initial typing was principally morphology-based (NBLAST) and generated a pool of cross-matched types for uniquely identifiable, often large neurons such as MBONs, uniglomerular olfactory projection neurons, or peptidergic neurons. This provided a scaffold on which to compute connectivity-based similarities between neurons from the different datasets. The connectivity-based approach was often required to make matches at the level of terminal cell types. In order to accelerate

running a neuron matching pipeline, we developed R and Python tools to generate and efficiently review large-scale clusterings (see *coconat*, *cocoa* and *bigclust* in Table 2). Connectivity and skeletons (NBLAST) for the male CNS, MANC and the hemibrain was principally obtained from neuPrint. For FlyWire, we used the same L2-based skeletons as in Schlegel *et al.*[31]. For connectivity, we used the new FlyWire synapse predictions[165] (materialization version 783) available from https://codex.flywire.ai.

The above matching pipeline was run iteratively: cell type labels were added/refined and then used to update the connectivity similarities. While the terminal cell typing was primarily connectivity-based, we frequently used NBLAST to cross-check labels. Matches to each of the other datasets are recorded in a set of fields in neuPrint: `hemibrainType`, `flywireType`, `mancType` and `mancGroup`. For cases when male CNS neurons match multiple types in the other dataset, the types are shown separated by a comma. The field `matchingNotes` includes, when necessary, relevant information for the cross-matching or typing. The primary `type` annotation represents the consensus type across all matched types. In a small number of cases, we modified existing types by defining a finer resolution subtype, merging two or more types , renaming the type or creating new types. For example, some of the tentative `CBXXXX` introduced with FAFB/FlyWire were given new names following the hemibrain's convention of `{main input region}{number}`. New male-specific types also follow this convention with an additional '`m`' suffix, e.g. "`SIP136m`".
The field `group` relates to matching within a type in this dataset and represents a more granular label than `type`. In some cases, we expect the differences we observe between groups of a type to be the result of natural variation and not stereotypical differences observed in all individuals. The field `instance` merges together `type` and `somaSide` or `rootSide` for sensory neurons.

Optic lobe typing

Cell typing for the left optic lobe largely followed the methods described in Nern *et al.*[36], combining morphological similarity with connectivity. Extensive comparisons were made to the typed cells of the right side, greatly accelerating the process compared to the previous *de novo* cell typing effort. For Extended Data Fig 4A and 4B we retain the cell type groups introduced in Nern *et al.*[36]: optic neuropil intrinsic neurons (ONINs), optic neuropil connecting neurons (ONCNs), visual projection neurons (VPNs) and visual centrifugal neurons (VCNs). We note that Fig 4 combines ONINs and ONCNs into one group OLINs. We are omitting the category of cell types grouped as "other" in Nern *et al.*[36] in Extended Data Fig 4A and 4B, as these cells are central brain neurons with minor optic lobe connectivity, and in many cases, while present in both hemispheres, do not have synapses in both optic lobes. The latter difference may be due to natural variability or reflect differences in precise boundaries of neuropil ROIs between hemispheres. The new, complete dataset provides a more complete description of the connectivity and brain region innervation of optic lobe associated cell types with synapses outside the (right) optic lobe. We found that three previously assigned[36] optic lobe cell types were present in only one hemisphere (or, in one case, only had a marginal match between the candidate cell on each side) and appear to be also absent from other datasets. These cases may represent aberrant cells of unknown type rather than well-defined types.

Sensorimotor information flow analysis

Long-range flow of information from sensory inputs to motor neurons was assessed via maximum flow analysis of the synaptic graph. Unlike analyses of indirect connectivity[183,184], graph traversal[64], or dynamics of indirect connectivity traversal (influence)[158] from only a source population of neurons, maximum flow can yield a distinct measure of information flow for each pairing of sensory source and motor sink populations. This analysis is also suited to long-range information flow, since maximum flow values do not necessarily exponentially attenuate like most multiplicative indirect connectivity measures. However, a limitation of maximum flow is that it does not identify alternate routes with equal or slightly less total flow value, so negative inferences about information flow based on low maximum flow values must be made with caution. Note that information flow does not consider the sign of interactions, i.e., neurotransmitter predictions were not considered in this analysis.

Maximum flow was computed for each combination of sensory source modality class annotation and motor domain subclass annotation. Efferents, endocrine neurons, and other nervous system outputs were not included. Input-normalized synaptic connectivity was used as edge capacities. Pseudo-source and -sink nodes were added to the graph with unit capacity connections to all source and from all sink neurons, respectively. All other inputs to sources and outputs from sinks were ignored. Thus the upper bound of each potential maximum flow was the minimum of the number of source and sink neurons. Maximum flow was computed using Dinic's method[47] on a sparse graph representation[185], with floating point edge capacities in [0, 1] discretized into integral capacities in [0, 10000] and flows renormalized to [0, 1] after computation.

For each neuron, preference for a sensory modality was computed as the mean flow through the neuron across all maximal flows from that sensory source to all motor domain sinks. Likewise a preference score for motor domains for all neurons was computed as a mean over all flows from all sensory modality sources. Overall sensory or motor specificity for each neuron was computed as the maximum preference normalized by the sum preference for all sensory modality preferences and motor domain preferences, respectively. A corresponding combined sensorimotor specificity score was computed as the maximal flow value through a neuron normalized by the sum flow for all pairs of sensorimotor flows.

Due to the large number of abdominal motor neurons and their distance from most sensories, flows targeting them often spread broadly over neck connective neurons and caused these neurons to have relatively high preference values for the abdominal domain. To aid motor domain preference analysis for this population, a separate maxflow analysis was performed with the same sensory and motor annotation categories, except with abdominal motor neurons partitioned into separate domains for each annotated neuromere. This flow was not used for any other purposes; all other mentions of the sensorimotor flow analysis refer to the version with a single abdominal motor domain.

Analysis and visualization of sequential relationships in flows was performed using a pseudo-layering order, where neurons are assigned a layer value preferring to be one greater than the layer value of their flow inputs, weighted by the input-normalized flow value. Since flow is a directed acyclic graph, these layer assignments for all neurons, l, are

computed using the (pseudo-)inverse of the Laplacian of the input-normalized flow adjacency matrix, *F*:

$$(\vec{l} + \mathbf{1})F = \vec{l}$$
$$\vec{l} = -\mathbf{1}F(F - I)^{-1}$$

Sensorimotor clusters

For analysis of sensorimotor flow structure, descending and ascending neurons were clustered on the basis of a UMAP embedding of their sensorimotor flow. For clustering, the embedding was generated with 20 neighbors and a minimum distance of 0, using Euclidean distance. Clustering was performed on the mean sensorimotor flow aggregated by neuron type, projected into this embedding. Clustering was performed by simple k-means, with the number of clusters selected from a parameter sweep between [2, 60] maximizing the silhouette score. Cluster labels were reordered by clustering them via average agglomerative linkage of the cosine distance of their concatenated incoming and outgoing cluster connectivity.

Behavioural category compatibility of clusters was computed by multiplying the mean sensorimotor flow matrix of each cluster with a compatibility matrix for each behavioral category. Because the purpose was to demonstrate ease of interpretation of sensorimotor flow as it relates to putative function and behavioral hypotheses, rather than produce an optimal predictive algorithm, the compatibility matrices were manually constructed using simple rules of which sensorimotor pairings are likely predictive of compatibility with which behaviours. For those that are, those entries in the compatibility matrix are 1, while all others are 0. These pairing rules are as follows: for VNC sensation, any flow originating from gustatory, tactile, or proprioceptive modalities; for escape, any flow originating from vision targeting the legs or wings; for feeding, any flow originating from gustation or olfaction not targeting the abdominal domain, and any flow targeting the proboscis; for flight, any flow targeting the wings or halteres; for grooming, any flow originating from mechanosensory or tactile modalities targeting proboscis, neck, or front leg domains; for reproduction, any flow targeting the abdominal domain; for walking, any flow originating from any mechanosensory modality targeting leg domains. Both the compatibility and flow matrices are L_1 normalized before multiplication.

Axon-dendrite splits

Neurons were split into axons and dendrites (Fig 2) using the synapse flow centrality algorithm from Schneider-Mizell *et al.* [186] as implemented in *navis* (see Table 2). In brief, for a given neuron we associate its in- (postsynapses) and outputs (presynapses) with the neuron's skeleton. For each input we draw a path to each output and count the number of paths going through each segment of the skeleton. The segment(s) with the highest "flow" typically represent the link between axon and dendrite. Removal of the linker results then splits the neuron into axon and dendrites. Splits for neurons shown in Fig 2 were manually confirmed.

Effective connectivity

We first find direct and two-hop paths from all visual projection neurons (VPN) to either descending neurons (DN) that are sexually-dimorphic or -specific, or descending neurons for which there is existing research on the function of the cell type. We next filter the paths for both male and female, such that all direct connections are stronger than 1% of the input of the postsynaptic cell type. We further select from the filtered paths, ones that are unique to one sex, by removing paths that exist in the brain of the other sex, regardless of connection weight. We finally select only the paths that contain at least one sexually-dimorphic or -specific cell type.

We calculate the effective connectivity based on the selected paths: if the VPN connects directly to the DN, we use the connection strength. If the connection is through an intermediate neuron (i.e. two-hop), we use the square-root of the product of the connection weights.

For Extended Data Fig 4A, panel h, we extract all the direct and two-hop connections from visual projection neurons in Fig 4I, to descending neurons with known functions or sexual dimorphism. We then filter the pathways such that the direct connections are stronger than 1% normalized input of the postsynaptic cell type.

Both the paths extraction and plotting used methods from the Connectome Interpreter.

Edge normalization

Connections are either input- or output-normalized as defined in the text and figure legends.

Input normalization quantifies the relative contribution of each presynaptic partner to a postsynaptic neuron's total input. For a connection from neuron A to neuron B, input normalization is calculated as:

Input normalized strength = (synapses from A→B) / (total synapses received by B)

Output normalization quantifies how a presynaptic neuron distributes its synaptic output across its postsynaptic targets. For the connection from neuron A to neuron B, output normalization is calculated as:

Output normalized strength = (synapses from A→B) / (total synapses given by A)

Input normalization reveals the relative influence of individual presynaptic partners on their downstream targets, while output normalization reveals the specificity and distribution of synaptic outputs.

Definition of dimorphic edges

To define edges as either dimorphic or isomorphic (Fig 8), we first constructed a type-to-type graph for all cross-matched neurons with arbours in the central brain: superclasses `ascending_neuron`, `cb_intrinsic`, `cb_motor`, `cb_sensory`, `descending_neuron`,

`endocrine`, `visual_projection` and `visual_centrigufal` for the maleCNS and corresponding superclasses for FAFB/FlyWire. Connections made in the ventral nerve cord (VNC) of the male CNS were excluded. For FlyWire, we used the new synapse predictions[165] for materialization version 783 (available from Codex).

Connection weights (i.e. number of synapses) were divided up between the left and right hemisphere using the source neuron's soma (`somaSide`) as point of reference. For the small number of unpaired medial neurons that belong to neither side of the brain, we used the target's side if possible. For connections between unpaired medial neurons (i.e. where neither source nor target belong to the left or right hemisphere), we split the weight evenly between left and right. For sensory neurons, we used the side of the nerve through which their axons enter the nervous system. To align connection weights between the male and female dataset, we fitted a PCA to the data (Extended Data Fig 8d) and scaled the male weights by its slope (0.581). This produced a table like this:

		weight in male (scaled)			weight in female		
type_pre	type_post	weight_total	weight_left	weight_right	weight_total	weight_left	weight_right
AVLP532	CL110	10.45	5.81	4.64	20	12	8

To extract connections that are significantly different between male and female we used a standard t-statistic, i.e. the ratio of the difference in a number's estimated value from its assumed value to its standard error. The t-statistic t_{AB} for a connection between cell types A and B is defined as:

$$t_{AB} = \frac{(\bar{\chi}_m - \bar{\chi}_f)}{s_p \times \sqrt{\frac{1}{n_m} + \frac{1}{n_f}}}$$

where $\bar{\chi}_m$ and $\bar{\chi}_f$ are the means between the number of synapses connecting A and B on the left and right hemisphere in male (m) and female (f), respectively.

The pooled standard deviation s_p is defined as:

$$s_p = \sqrt{\frac{(n_m - 1)s_m^2 + (n_f - 1)s_f^2}{n_m + n_f - 2}}$$

where s_m and s_f are the standard deviations over the number of synapses between A and B for the left and right hemispheres in male and female, respectively. The number of observations, n_m and n_f, is 2: one from the left and one from the right hemisphere.

From the t-statistic, p-values were calculated using a two-sample t-test with 3 degrees of freedom as implemented in `scipy.stats.sf` [185]. The resulting p-values were adjusted to control the false-discovery rate using the Benjamini-Hochberg procedure, implemented in `scipy.stats.false_discovery_control`.

We considered all edges with $p \leq 0.1$ to be potentially dimorphic. In addition to the raw p-value, we applied two additional filters: first, a threshold of > 30% difference between the (combined left and right) connection weight in male and female. Second, connections with ≤ 8 synapses (left and right combined) in the female and ≤ 11 synapses (before scaling) in the male were considered noise.

Graph traversal

We employed a probabilistic graph traversal model first published in Schlegel *et al*. [64] to calculate the distance from sensory inputs for isomorphic, dimorphic and sex-specifc neurons (Fig 3l). Using a pool of all sensory neurons as seeds, the model pulls direct downstream partners and repeats the process until all nodes in the graph have been traversed. We used a linear function to determine the probability of traversal such that if neuron A makes up 30% or more of neuron B's inputs, there is a 100% chance of traversal. The chance of traversal for any neuron outside the pool connected to a neuron already in the pool is independent. We repeated the traversal 10,000 times and calculated the layers as the mean across all runs.

Olfactory system analysis

Sensory neurons are often difficult to reconstruct due to their fine calibre particularly as they cross the antennal commissure and artefacts likely associated with truncation of their axons during specimen preparation. RNs in the male CNS were no exception with reconstruction status summarised in Extended Data Fig 6a. Almost all RNs are bilateral (projecting to homologous glomeruli in left and right antennal lobes) with the side of entry into the neuropil annotated as `rootSide`. However some neurons could not be followed as they crossed over the midline leaving two separate fragments for which the side of origin was uncertain. When quantifying the number of RNs we use the term 'neurons' when we have accounted for the duplication of bodies where their side of origin is unknown, and 'bodies' when we have not. However, even accounting for this, there appeared to be asymmetries in both neuron numbers and synapse numbers between the two hemispheres (Extended Data Fig 6b). For these reasons we opted to use the total number of RNs in our analysis rather than presenting an interhemispheric comparison (our approach in most other parts of the CNS). Furthermore, for most of our analyses, we were able to leverage the hemibrain dataset to provide an additional data point. However, this comparison was not satisfactory since ~50% of glomeruli in that dataset are truncated and/or have fragmented RNs [64].

To test whether ALPNs with high sex-specific or sexually dimorphic output (≥10% of presynapses; Fig 6g) differ in their odour input composition, we first assigned each ORN/uPN to one of five mutually exclusive valence categories (adapted from [64]). For bootstrapping, we resampled (with replacement) the remaining set of ALPNs 1000 times, and for each sample calculated the mean percentage input received from ORNs/uPNs in each valence category. This produced a bootstrap distribution of means per category, which we compared with the observed values for the high sex-specific/dimorphic output group.

Network analyses

Hierarchical community detection

The hierarchical community structure is determined to analyse the contributions of isomorphic and dimorphic/sex-specific cell types in the network structure. Here, we fit a nested stochastic block model (SBM) to the data to infer partitions of nodes by their network connectivity. The SBM is a generative model for networks in which nodes are partitioned into blocks (or groups), and edges are placed between blocks according to block-specific connection probabilities. Given a particular partition, the likelihood that the observed network was generated under the model can be computed. To identify the best partition, this inference relies on the minimum description length (MDL) principle: the best model is the one that provides the most concise description of the data. In practice, this involves jointly encoding (i) the model parameters and assumptions (e.g., the block structure and probabilities) and (ii) the data given the model. The description length, measured in bits, is minimized when the model strikes the best trade-off between complexity (number of parameters) and goodness of fit (how well it explains the observed network). Importantly, this balance means that it does not overfit noisy data as is the case for modularity maximization based approaches [187]. The hierarchical partitions and the number of communities inferred are optimal by the above criteria. The procedure was employed with male cell-type connectivity graph of the central brain, where the synapse counts (edge weights) are modelled with a discrete geometric distribution, as determined in the larval brain to be most optimal [188]. The graph-tool implementation was used to run the hierarchical block assignment [189], we first obtained a greedy nested block model assignment and performed 1000 iterations of 10 Markov Chain Monte Carlo (MCMC) merge-split sweeps to improve the solution [190].

Cluster enrichment analysis

Our hierarchical block structure provides a set of clusters which we evaluate for statistically significant enrichment in male-specific or dimorphic types. We used the hypergeometric distribution to assign each cluster a probability of randomly drawing at least the observed number of non-isomorphic types. We calculated this probability for each cluster across the whole hierarchy. Then, using the Benjamini-Hochberg method accounting for the false discovery rate (FDR), we designated clusters as enriched at $\alpha = 0.01$. We obtained 13 clusters at the highest granularity level.

Optic lobe analysis

Pale and yellow column identification

Medulla columns were classified as pale or yellow using both anatomical markers and synaptic connectivity, essentially following the previously described procedure [36]. Briefly, R7 photoreceptors were classified based on connectivity patterns with Dm8a/Tm5a (yellow) versus Dm8b/Tm5b (pale) cell pairs, and the presence of aMe12 and Tm5a branches in a column, used as anatomical markers. For most columns, column classification based on morphology and connectivity markers was consistent, the remaining cases were assigned based on the balance of evidence and sometimes left as ‘unclear’. As previously reported for the right optic lobe, we found some photoreceptors to be missing or incompletely reconstructed; the corresponding columns were assigned based on the anatomical markers alone. The main difference in the new dataset is that systematic additional proofreading of aMe12 cells, including in the right optic lobe, enabled us to identify many more of the

aMe12s' fine vertical branches, which serve as the most reliable known markers of pale-specific columns [191], achieving substantial improvement on the prior effort (summarized in Extended Data Fig 5 of Nern *et al.* [36]). However, even with these improvements, the new analysis still revealed greater complexity than previously appreciated: the available anatomical markers are insufficient to place all columns (excluding edge and DRA columns) in two uniform groups, pale or yellow (as also discussed in the Methods of Nern *et al.*[36]). Making the assuming that with the new reconstructions the set of aMe12 branches is now close to complete, we implemented a refined classification scheme that identifies likely yellow columns (i.e. columns without aMe12 vertical branches) as two subtypes – those with and without Tm5a branches/connections. This updated column assignment yields column counts consistent with previous expectation [191–193] while minimizing the number of 'unclear' unassigned columns (Extended Data Fig 4Bf-j).

Neuron visualization

Three-dimensional neuron renderings for showing whole-brain projection views and optic lobe slice-views (Fig 4, Extended Data Fig 4B) were generated using the Blender-based pipelines developed in Nern *et al.*[36].

Comparison of edge weights in the optic lobes

Plots showing the percentage of inputs to the postsynaptic cells for pairs of connected cell types (for comparing males and females) or instances (for comparing the left and right optic lobe) in the optic lobes (Extended Data Fig 4l, Extended Data Fig 4A), include only connections with a combined synapse count above a threshold on at least one side of each comparison. Connection pairs that show high technical variability (e.g. those involving photoreceptors or cells in the lamina) or are entirely absent from one side of a comparison (i.e. sex-specific or present in only one optic lobe) are also omitted.

Eye maps for visual projection neuron spatial analysis

For the spatial coverage heatmaps of visual projection neurons in Fig 4 and Extended Data Fig 4Ae, we first mapped the spatial locations of input synapses to column ROIs (described below). This spatial pattern together with the synapse count in each column were then visualized on a new eye map, representing the visual field of the compound eyes. This eye map was based on the data and methods of Zhao *et al.* [78], but extended to accommodate the medulla column ROIs in the male CNS brain (detailed in Zhao *et al.*, ms in prep).

Cell Type Explorer interactive web resources

The Cell Type Explorer web resource was substantially updated to include bilateral optic lobe analyses and expanded to encompass connectivity summaries for all central brain neurons. The web interface now features enhanced interactivity, enabling users to filter and sort connectivity tables and browse cell types across the entire male CNS connectome. The right optic lobe web resource will remain at its original URL: https://reiserlab.github.io/male-drosophila-visual-system-connectome/, while the updated version is hosted from https://reiserlab.github.io/celltype-explorer-drosophila-male-cns/.

Column and layer ROIs

Column and layer creation for the left optic lobe

Columns and layers for the left OL were created using similar methods to the right OL[36], with one major difference: neurons were assigned to columns and hexagonal coordinates

automatically rather than manually. We also updated several parameters used in column and layer creation and in the T4-to-Mi1 assignment for columns and layers in the LOP. We used these new parameters to also update the columns and layers in the right LOP.

Automated column assignment via community detection

To automatically assign columnar neurons in the ME to columns, we selected all 10626 neurons of cell types L1, L2, L5, Mi1, Mi4, Mi9, C3, Tm1, Tm2, Tm9, Tm20 and T1 in the left OL. For the right-side ME columns we had used these columnar cells in addition to C2, L3 and Tm4, but our previous analysis[36] showed that these cell types are less columnar than the others (smaller fraction of their synapses could be assigned to single columns, with median < 0.65).

The key idea behind the automatic column assignment is that columnar neurons within a column should be more strongly connected to each other than to columnar neurons in other columns. Such an assignment can be achieved via community detection algorithms of networks. We applied generalized modularity maximization[194,195], implemented with the Leiden algorithm (https://leidenalg.readthedocs.io/en/stable/intro.html). Modules (or communities) are non-overlapping sets of nodes that maximize a function called generalized modularity. Intuitively, this function compares the observed connectivity with that of an averaged random network that has matched in/out-degrees, i.e., the same total number of outgoing and incoming connections for each pair of neurons; but the latter connectivity is also scaled by a parameter γ. If the observed connectivity between a pair of neurons is larger than that of γ times the averaged random network, neurons are more strongly connected than expected and are therefore likely to be part of the same module; if below, they are less likely. Theoretical work has shown that γ controls the total number of modules found by generalized modularity maximization [195] and that using a specific γ is equivalent to maximum likelihood estimation in certain stochastic block models with statistically similar communities[196]. In our application, we expect columns to form statistically similar communities, which makes generalized modularity maximization an appropriate choice of community detection algorithm.

The connectivity between the columnar neurons in the left ME determines the modules, and hence their column assignment. We removed weekly connected neurons (15 cells with ≤3 connections to any other columnar neuron or ≤10 total connections to other columnar neurons) and one clear merge error. We optimized the parameter γ by sweeping it over a wide range of values and observed how the number of modules changed. If robust modules exist, the number of modules should remain approximately constant over a range of γ's and be close to the number of columns in the right ME (892 columns). We used the leidenalg Python library (https://leidenalg.readthedocs.io/en/stable/intro.html) and the functions "Optimiser", "RBConfigurationVertexPartition", "optimize_partition", and "resolution_profile" with "resolution_range=(50,150)". We found that the number of modules changed more slowly around 880 modules. We picked γ=100 which gave 884 modules—the same as the number of L1 neurons in the left OL. (We note that 892 also equals the number of L1 neurons in the right OL.)

Since we will use these modules to divide the ME ROI into column ROIs (see below), we further required that all neurons must have synapses in the ME ROI; due to imperfections of the ME ROI, this removed 7 more neurons, leaving 10603 neurons. Of the 884 modules, 790 modules contained exactly one neuron per cell type. 58 modules contained less than 12 columnar cell types but up to 12 neurons, and 36 modules contained all 12 columnar cell

types but more than 12 neurons. Most of these 96 imperfect modules were at the boundary of the ME. Conversely, 113 neurons were over-assigned to modules (i.e., if for each module we picked a single assigned neuron per cell type, then 113 neurons were left over).

Hexagonal coordinate assignment and ROI creation

Column modules were assigned hexagonal coordinates by applying an algorithm developed to assign hexagonal coordinates to ommatidia of the fly eye[78]. This algorithm uses local difference vectors between a point and its 6 nearest neighbors (7 manually identified points) to find all the other neighbors and works reliably for nearly regularly spaced points. We applied this algorithm to the mean synapse positions of all columnar neurons in each module. We manually verified the assigned hexagonal coordinates and made ~10 manual re-assignments to edge columns. We removed 5 edge modules (outside of the ME ROI or duplicated), resulting in 879 column modules with hexagonal coordinates. Column ROIs were created using one neuron per cell type per hexagonal coordinate, with the same algorithm (and identical parameters) used for the right OL[36]. To make layer ROIs, we also applied the same algorithm as for the right OL but with slightly adjusted parameters: in the ME, we used “alpha=0.0004” and “fac_ext=1”; in the LO, “frac_peaks=0.75”, “alpha=0.0002”, “fac_ext=0.3”; in the LOP, “frac_peaks=0.85”, “alpha=0.0002”, “fac_ext=0.3”.

Extending the coordinate system to the LO and LOP

We relaxed the criterion for T4-to-Mi1 assignments from requiring all four T4 types to requiring at least three types to be assigned to an Mi1 neuron. This increased the valid assignments in the right lobula plate. These results are summarized in Extended Data Fig 4Bb. The number of layers on the left matches those on the right.

Sex-specific branch analysis

For the analysis of connectivity on sex-specific branches (Fig 8m-p), we manually placed annotations in Neuroglancer to define cut points that would separate sex-specific from isomorphic branches. We then split the neurons for each of the 46 types using `navis` (see Table 2) and associated their synaptic connections with either sex-specific or isomorphic branches using nearest-neighbor lookup. All splits were manually inspected to confirm correctness. Depending on whether the sex-specific branches represented the neurons’ dendrites or axons, we only quantified their incoming or outgoing connections, respectively.

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