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# Novelty detection in early olfactory processing of the honey bee, *Apis mellifera*

Hong Lei[1], Seth Haney[2], Christopher M. Jernigan[1,¤a], Xiaojiao Guo[1,¤b], Chelsea N. Cook[1,¤c], Maxim Bazhenov[2], Brian H. Smith[1] *

**1** School of Life Sciences, Arizona State University, Tempe, AZ, United States of America, **2** Department of Medicine, University of California, San Diego, CA, United States of America
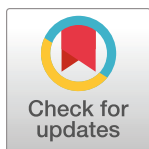
☉ These authors contributed equally to this work.
¤a Current address: Department of Neurobiology and behavior, Cornell University, Ithaca, NY, United States of America
¤b Current address: State Key Laboratory of Integrated Management of Pest Insects and Rodents, Institute of Zoology, Chinese Academy of Sciences, Beijing, 100101, China
¤c Current address: Department of Biological Sciences, Marquette University, Milwaukee, WI, United States of America
* brian.h.smith@asu.edu

## Abstract

Animals are constantly bombarded with stimuli, which presents a fundamental problem of sorting among pervasive uninformative stimuli and novel, possibly meaningful stimuli. We evaluated novelty detection behaviorally in honey bees as they position their antennae differentially in an air stream carrying familiar or novel odors. We then characterized neuronal responses to familiar and novel odors in the first synaptic integration center in the brain–the antennal lobes. We found that the neurons that exhibited stronger initial responses to the odor that was to be familiarized are the same units that later distinguish familiar and novel odors, independently of chemical identities. These units, including both tentative projection neurons and local neurons, showed a decreased response to the familiar odor but an increased response to the novel odor. Our results suggest that the antennal lobe may represent familiarity or novelty to an odor stimulus in addition to its chemical identity code. Therefore, the mechanisms for novelty detection may be present in early sensory processing, either as a result of local synaptic interaction or via feedback from higher brain centers.

## Introduction

Animals are constantly bombarded with stimuli to which they must assign meaning [1,2]. To assess the importance of a stimulus, information needs to be retained in a limited capacity 'working memory' [3–5] for a short period of time. Working memory serves as a preprocessor and an important interface between sensory processing and higher order cognitive functions [6], and the ability to shift the focus of limited attention away from meaningless stimuli and toward potentially meaningful ones is very important. Accordingly, associations between stimuli held in working memory and important events–such as food or threats–can make stimuli more salient [7,8], whereas the lack of any salient association reduces an animal's attention to

inconsequential stimuli. The latter occurs in Latent Inhibition [9–11], where animals habituate to repeated stimulation by 'familiar' stimuli. The process of familiarization can also lead animals to react strongly to 'novel' stimuli being experienced for the first time. Although novelty detection can be measured by heightened behavioral responsiveness to a novel stimulus, it is important to further investigate where and how novelty detection might be implemented in neural circuits in the nervous system.

The primary olfactory center, the antennal lobe (AL) in insects and olfactory bulb in vertebrates, is well situated to perform critical odor preprocessing and to categorize olfactory inputs on glomerular activity maps for odors [12,13]. Within each glomerulus, extensive synapsing occurs between sensory neurons and interneurons, and between the interneurons themselves. Both associative and non-associative plasticity at different synapses in the AL [14–19] bias odor representations to allow animals to focus a limited attention capacity on salient, predictive stimuli [9,17,20,21]. This plasticity is driven, in part at least, by release of octopamine from Ventral Unpaired Medial neurons in the subesophageal ganglion of the brain when the honey bee feeds on sucrose [22,23]. Attention is also modulated by novelty and familiarity, which are experience-dependent qualities. The same odor stimulus can be novel or familiar to an animal depending on the animal's previous experience. There are no specialized novelty or familiarity sensing neurons on the antennae or known specialized glomeruli in the AL to mark odors being novel or familiar. Therefore, novelty and familiarity would be new qualities that are created within the neural networks in the AL or elsewhere in the brain and fed back to the AL.

In the fruit fly, *Drosophila melanogaster*, it has been shown that synaptic plasticity mediated by GABAergic mechanisms in AL circuits underlies a stereotypical response to familiar odors in an odor-specific manner [24], but it is unclear if and how the same circuit motif affects responses to novel odors. On the other hand, the mushroom bodies, which are the third-order synaptic centers along the olfactory pathway and important centers for learning and memory, generate distinct response patterns to both familiar and novel odors [25]. In particular, one type of mushroom body output neuron, namely α'3 MBONs [26], decrease response magnitude to familiar odors over repeated stimulations but respond strongly to novel odors. The novelty detection requires participation from a dopaminergic neuron innervating the same structure [25]. However, it is not known whether the neural code for novelty and familiarity is generated only in the mushroom bodies, or whether it can be reflected in earlier circuits, such as the AL, through intrinsic synaptic modifications or via feedback from the mushroom body.

Here, we show in the honey bee that AL local and projection neurons can be potentiated to novel odors and adapted to familiar odors after unreinforced exposure—familiarization—to an odor. This provides a neural coding scheme to categorize odors as being novel or familiar in addition to the glomerular coding patterns for chemical identities.

## Results

### Different antenna movement to stimulation by novel and familiar odors

We began by asking if there are observable behaviors by which honey bees exhibit novelty detection. We used a familiarization protocol called Latent Inhibition [11], which has been established in proboscis extension response (PER) conditioning of honey bees [10,27], to familiarize subjects to one of two odors (Fig 1A). Previous PER studies have shown that 20 to 40 presentations of an odor without reinforcement retards learning to associate this now familiar odor with reinforcement relative to a different, novel odor [10]. We now evaluated how familiarization might be exhibited in honey bee antennal movements to odors. The bees were restrained in harnesses that are commonly used in procedures for studying nonassociative, associative and operant conditioning in PER [28], and which allows for monitoring of
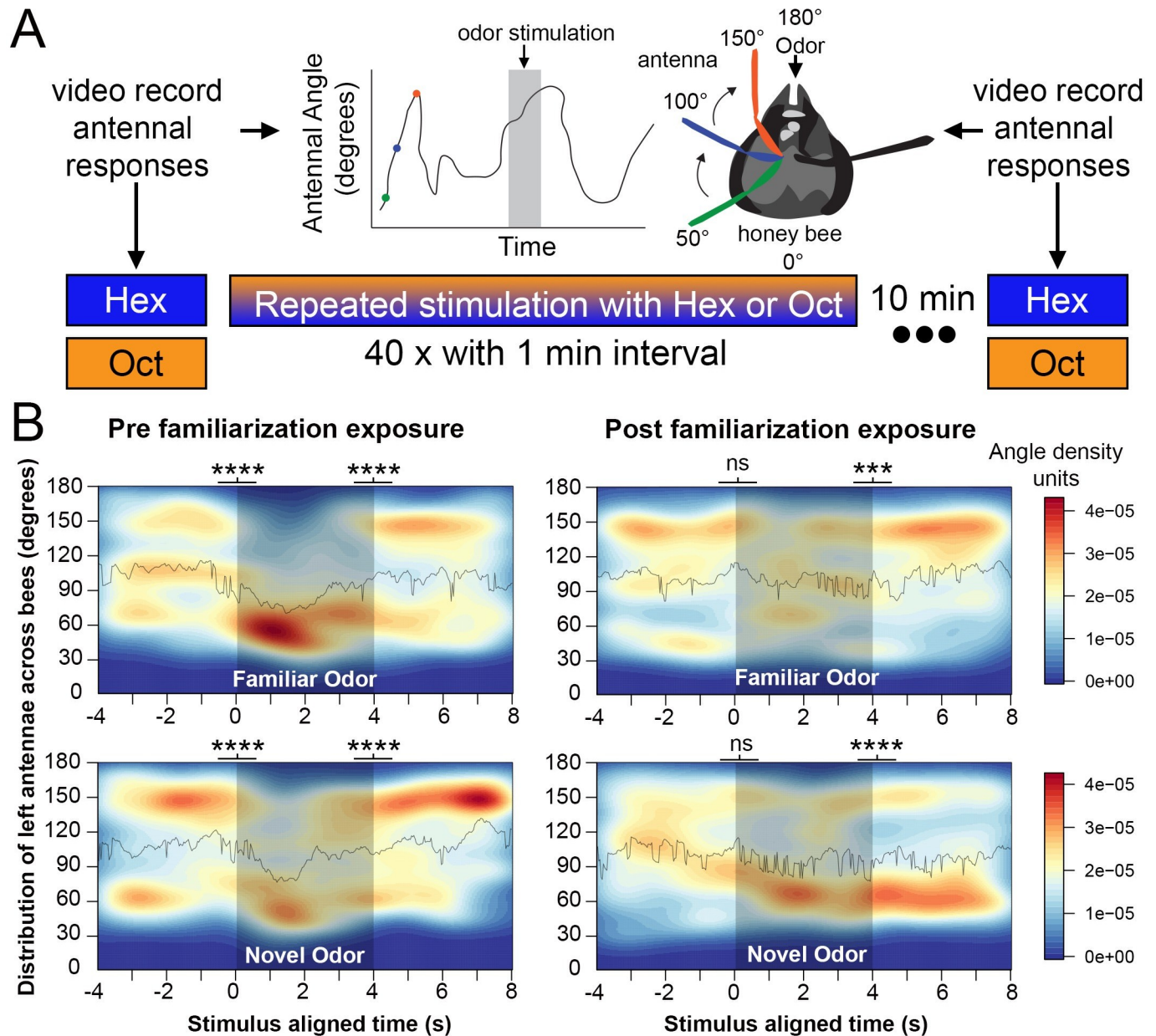
**Fig 1. Left antenna responses to novel and familiar odors.** (**A**) The familiarization protocol using either Hexanol or Octanone as the repeatedly presented unreinforced odor stimulus. Tests were performed with each odor prior to and after familiarization. The headspace is divided into a clockwise circular range of 180 degrees for each antenna. (**B**) The average distribution densities of left antennae's angular positions in response to odors before the familiarization process (left column plots) and 10 min after the familiarization process (right column plots). Plots are aligned by odor onset over 12 s, which includes 4 sec segments before, during and after odor delivery (360 frames; N = 24 animals, 13 Hex exposed, 11 Oct exposed). In both columns, the top plot shows responses to the familiar odor and the bottom plot shows responses to the novel odor. The solid line in each plot represents the mean angle of the left antenna across all 24 bees for each respective odor. The shaded region indicates the period during odor stimulus presentation. The colored scale to the right of the plots shows the standardized Kernel density scale across all plots. For statistical comparisons angular position was normalized by calculating the difference in the left antenna's angular position at all time points from the mean antennal angle (when no odor present) across the three time-sections for each bee and odorant presentation. Statistical analyses: Two-way ANOVA, difference measure~ time period * odor, df = 2, n = 24, Tukey HSD post-hoc comparison, asterisks indicate statistical significance, **** $p < 0.00001$, ns indicates not significant.

antennal movements. Restrained honey bees actively scan the air flow around them with their antennae to sample headspace volatiles [29]. The patterns of these movements can be modified

by appetitive conditioning [30,31]. Using video tracking [29], we recorded, frame-by-frame, the angular positions of each of the antennae in a 180˚ space on each side of the head. We recorded positions continuously in 4 sec blocks before, during, and after exposure to two odorants, 1-hexanol (hex) and 2-octanone (oct) (Fig 1A).

Prior to becoming familiar with the odors, honey bees responded to both odors similarly (Fig 1B). In the period before the odor is presented, honey bees sweep their antennae forward and backward and the antennal positions reflect a fairly equal probability of being in typical areas of the space, i.e. equal forward, central and backward distribution. The backward position is comparable to a lifted antenna position in bee's natural posture when walking or flying. During the 4 sec of odor presentation, the antennae are mostly held backward, and during the 4 sec just after the odors are switched off the antennae return to a more typical distribution across the space (Fig 1B). Transitions from before-to- during and from during-to-after were all significant. The asterisks at the border between different time sections in Fig 1B indicate that the difference in antennae position from the mean antennal angle (when no odor was present) is statistically significant between the time blocks (two-way ANOVA, n = 24, Tukey HSD post-hoc comparison, **** $p < 0.00001$).

In contrast, after the familiarization process the same transitions differed for the familiar and novel odors (Fig 1B). The now familiar odor no longer elicited a sharp transition from the before-to-during time segment, and the more diffuse distribution during odor presentation shifted to the more forward position after termination of the familiar odor. However, the 'novel' odor showed the expected transition from before-to-during the odor presentation. Importantly, the antennae maintained the backward position even after the novel odor was terminated. Movements of the right antennae also showed similar patterns to the novel odor in that the pattern changed in the same way the left antenna movements changed when the novel odor was presented and did not change when the novel odor was terminated (S1 Fig, bottom right). However, the diminished response to the familiar odor was less pronounced (S1 Fig). Difference in movement induced by odors between left and right antenna has been reported [32], and these differences could be correlated with their non-symmetrical (or lateralized) sensory responses to odors [33,34]. The backward movements in the current study, and in particular the persistence in those movements to a novel odor, imply that they are involved in odor detection, and we interpret them as indicating the degree of novelty or surprise in a new odor.

## Familiarity and novelty effects on PNs and LNs

We then sought neural correlates of the novelty in the AL. In the insect AL [35], all of the olfactory receptor neurons in an antenna that express the same receptor project axons to the same area (glomerulus) of the AL, where they synapse with PNs that relay activity to higher brain centers such as the Mushroom Body. Different types of Local Interneurons (LN), which are mostly GABAergic, interconnect glomeruli and set up local processing in the AL. We recorded two hundred seventeen units from the left AL of 19 bees before and after inducing familiarity using the same familiarization protocol as above (Fig 1A) [27]. These extracellularly recorded units were classified into probable PNs (N = 87) and LNs (N = 115) based on the statistical properties of their spiking patterns. Specifically, following methods outlined by Meyer and colleagues [36], we assessed the variation of the inter-spike interval within a trial, the variation of spike count across trials, the change in firing rate due to the stimulus, and the lag-time to response (see Methods, Fig 2A and 2B). These features were sufficient to classify two different categories of units whose properties agreed with morphologically identified PNs and LNs (Fig 2C–2E and see Meyer et al. 2013). Some units (N = 15) were not able to be classified because of low spike counts and not included in analysis.
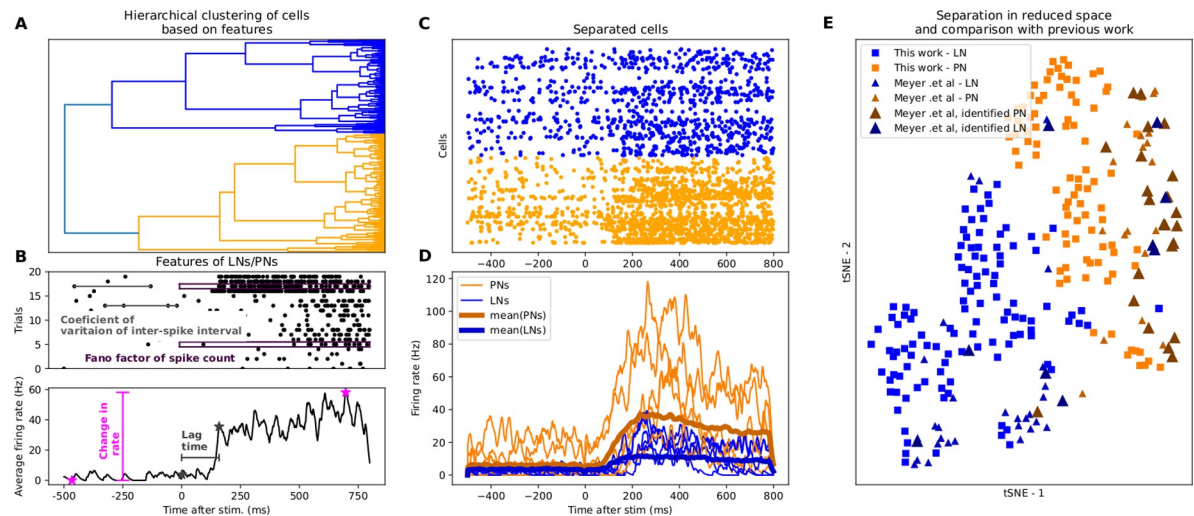
**Fig 2. Separation of PNs and LNs using a statistical procedure outlined in [1].** (**A**) Separation of LNs and PNs using hierarchical clustering (see Methods) into LNs (blue) and PNs (orange). (**B**) Explanation of cell-based features used for clustering (see Methods) based on spike times (top) and response rate (bottom). (**C**) Spike rasters and, (**D**) firing rate time courses of separated cells. (**E**) Cell-based features visualized in reduced space using tSNE (t-distributed Stochastic Neighbor Embedding) [4].

We quantified a neuron's 'net response' to odor by calculating a ratio of the amount of stimulus-evoked response relative to the spiking activities for an equivalent period immediately prior to stimulation (see Methods). This metric allows a closer comparison to previous experiments using calcium imaging, where $\Delta F/F_0$ was calculated [15,37]. We compared the averaged responses of both PNs and LNs separately to the familiar and novel odors before and after familiarization. We first pooled the stimuli into familiar or novel categories irrespective of the specific odors (Hex or Oct) used in the familiarization process. As a result, 50% of PNs (Fig 3A1 and 3B1) and 56% of LN's (Fig 3A2 and 3B2) showed stronger responses to the novel odor. On average, for both PNs and LNs there was a reduction in response to the familiar odor and an increase in response to the novel odor after familiarization relative to before (Fig 3C1 and 3C2). To test the significance of this pattern, we performed 2-way ANOVA using the log normalized pre- and post-familiarization responses as one factor and responses to familiar and novel odors as the second factor. For both PNs and LNs the interaction between the two main effects was significant (PNs: F = 4.06, p < 0.05; LNs: F = 4.7, p < 0.05). That is, the decrease in response to the familiar odor between pre- and post-familiarization significantly contrasts with an increase in response to the novel odor observed between pre- and post-familiarization. This pattern was largely confirmed with post-hoc t-tests (Fig 3). For both PNs and LNs the increase in response to the novel odor was significant. The decrease in response to the familiar odor presented a trend for the PNs and was not significant for the LNs. These data suggest that novelty potentiates responses in PNs and LNs, and familiarity may decrease responses in PNs.

To further visualize the response patterns in PNs and LNs, we plotted the peristimulus time histograms generated by the Hex-familiarized PNs and LNs (Fig 3D1, 3D2, 3E1 and 3E2). Comparison of PN (D1 and E1) and LN (D2 and E2) responses pre- and post-familiarization reveal changes in some units in responsiveness to the novel odor, which is the basis for the average differences in responses (C1 and C2). However, there is clearly variation among the neurons in their capacity to differentiate familiar from novel odors, thus necessitating analyses based on further sub-classifications among PNs and LNs.
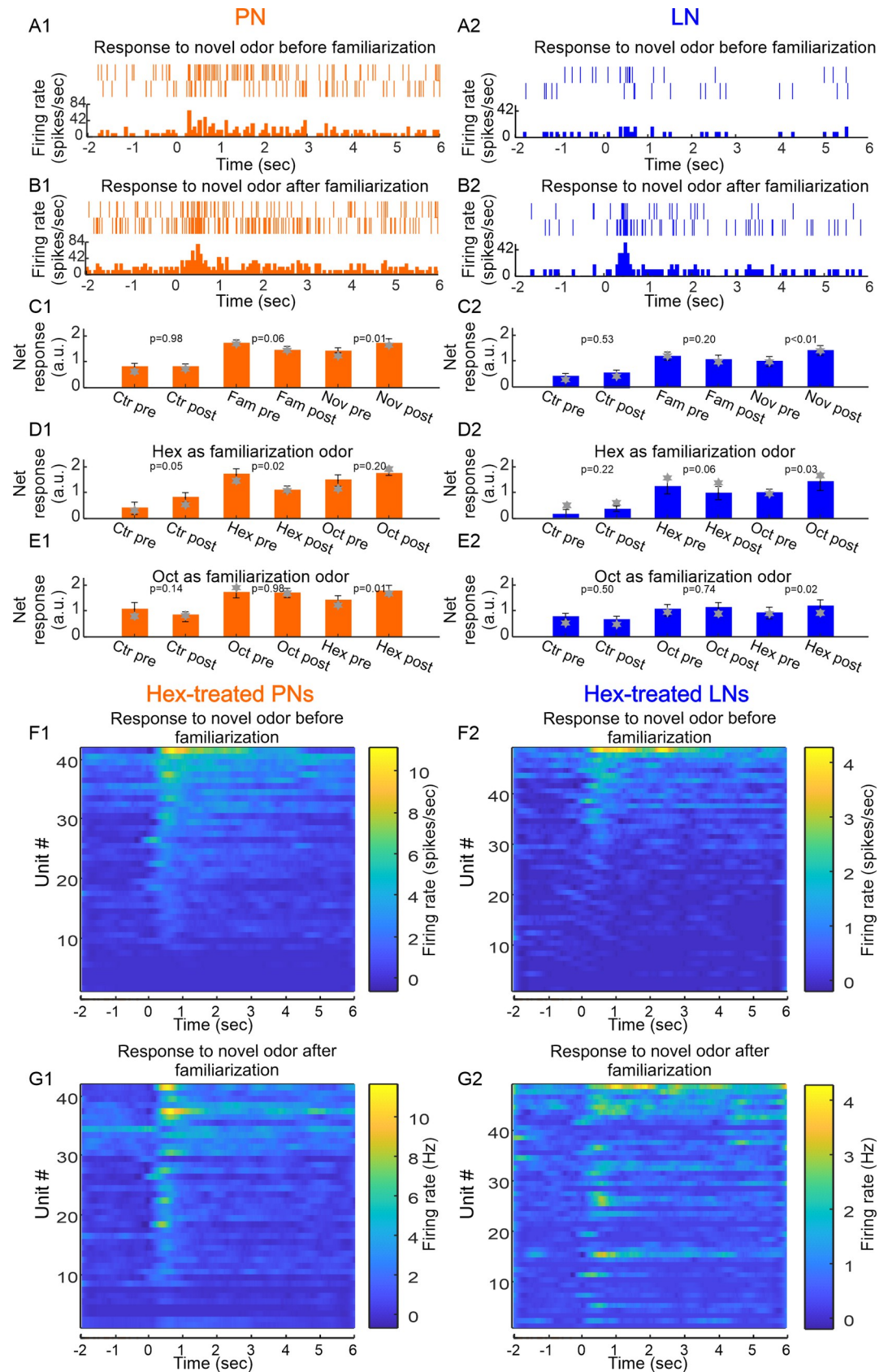
**Fig 3. Novelty and familiarity is evident in both PNs and LNs.** Familiarization potentiates the responses of PNs (**A1, B1**) and LNs (**A2, B2**) to novel odor (Hex), evident by the raster plots (top of each panel) and peristimulus time histograms (PSTHs) (bottom of each panel). The odor was delivered at time zero, lasting for 4 sec. The mean response of all PNs (orange bar graph, **C1**; log transformed) shows a decreasing trend to the familiar odor from pre- to post-familiarization (middle two bars, mean ± S.E., $p = 0.06$, $n = 87$, paired-t test), and a significant increase to the novel odor (right two bars, mean ± S.E., $p = 0.01$, $n = 87$, paired-t test); there is no significant change in response to the solvent control (left two bars, mean ± S.E., $p = 0.98$, $n = 87$, paired-t test). In LNs (**C2**), the familiarity effect is not significant (middle two bars, log transformed; mean ± S.E., $p = 0.2$, $n = 115$, paired-t test) but the novelty effect is significant (right two bars, mean ± S.E., $p<0.01$, $n = 115$, paired-t test). No significance was detected to solvent control (left two bars, mean ± S.E., $p = 0.53$, $n = 115$, paired-t test). The grey stars in (**C1**) and (**C2**) marks the median value, which was used to establish rough equivalence to the mean, as would be the case for a normal distribution needed for parametric tests. The pseudo-colored PSTHs of all Hex-familiarized PNs (**D1, E1**), ranked low (bottom) to high (top) according to firing rate pre-familiarization (**D1**), show clear variation across units in the novelty effect before and after familiarization. The novelty effect appears to be even more variable among the Hex-familiarized LNs (**D2, E2**).

## Novelty and familiarity effects on response-based subtypes of PNs and LNs

A subset of PNs and LNs showed biased responses to Hex or Oct prior to familiarization (Fig 4A1 and 4A2). We therefore classified each PN and LN as either familiar-odor biased or novel-odor biased, based on which odor it showed a stronger response to and on which odor was eventually used for familiarization. We then evaluated novelty detection on these different subsets by calculating the change in response due to familiarization for the novel and familiar odors in either Hex-familiarized or Oct-familiarized PNs and LNs (Fig 4B1 and 4B2). For Hex-familiarized PNs, the novel odor was Oct and the familiar odor would be Hex, and visa-versa. In familiar-biased PNs, there were more neurons showing stronger response to the novel odor after familiarization, depicted by the positive median values of the $2^{nd}$ and $4^{th}$ boxes in Fig 4B1. In contrast, these PNs showed decreased response to the familiar odors after familiarization, depicted by the negative median values of the $1^{st}$ and $3^{rd}$ boxes. A similar pattern, i.e. increases in responses to novel odor and decreases in responses to familiar odor, was also observed in the familiar-odor biased LNs (Fig 4B2).

This pattern is statistically significant in both PNs (Fig 4C1; McNemar test, $p = 0.02$ for Hex-familiarized group; $p = 0.04$ for Oct-familiarized group) and LNs (Fig 4C2; McNemar test, $p<0.01$ for Hex-familiarized group; $p<0.001$ for Oct-familiarized group). These results indicate that neurons with a strong initial response to the familiarization odor showed the most dramatic changes both to the familiar and novel odors during the familiarization process (Fig 4B1, 4B2, 4C1 and 4C2). In contrast to the familiar-odor biased neurons, neither novel-odor biased PNs (Fig 4D1) nor novel-odor biased LNs (Fig 4D2) showed significant changes induced by familiarization (PNs: McNemar test, Hex-treated $p = 1.0$, and Oct-treated $p = 0.07$; LNs: McNemar test, Hex-treated $p = 0.62$, and Oct-treated $p = 0.51$).

These results imply that familiar and novel odors should become more distinguishable after the familiarization process among neurons for which Hex and Oct elicit strong responses. This prediction was verified by comparing the spatial separation between these two odors before and after familiarization in a coding space constructed from the first three principal components of PN population responses to familiar and novel odors (Fig 5A). Moreover, the largest separation occurred at the peak response after odor stimulation, as shown by the Euclidean distance curves calculated from the difference of PN population responses to familiar and novel odors before and after familiarization (Fig 5B).

## Discussion

Novelty detection suggests that it is important to quickly evaluate unfamiliar stimuli for the possibility that they may be associated with consequential events that promote or threaten survival. More attentional resources, for example, could then be devoted in a limited capacity
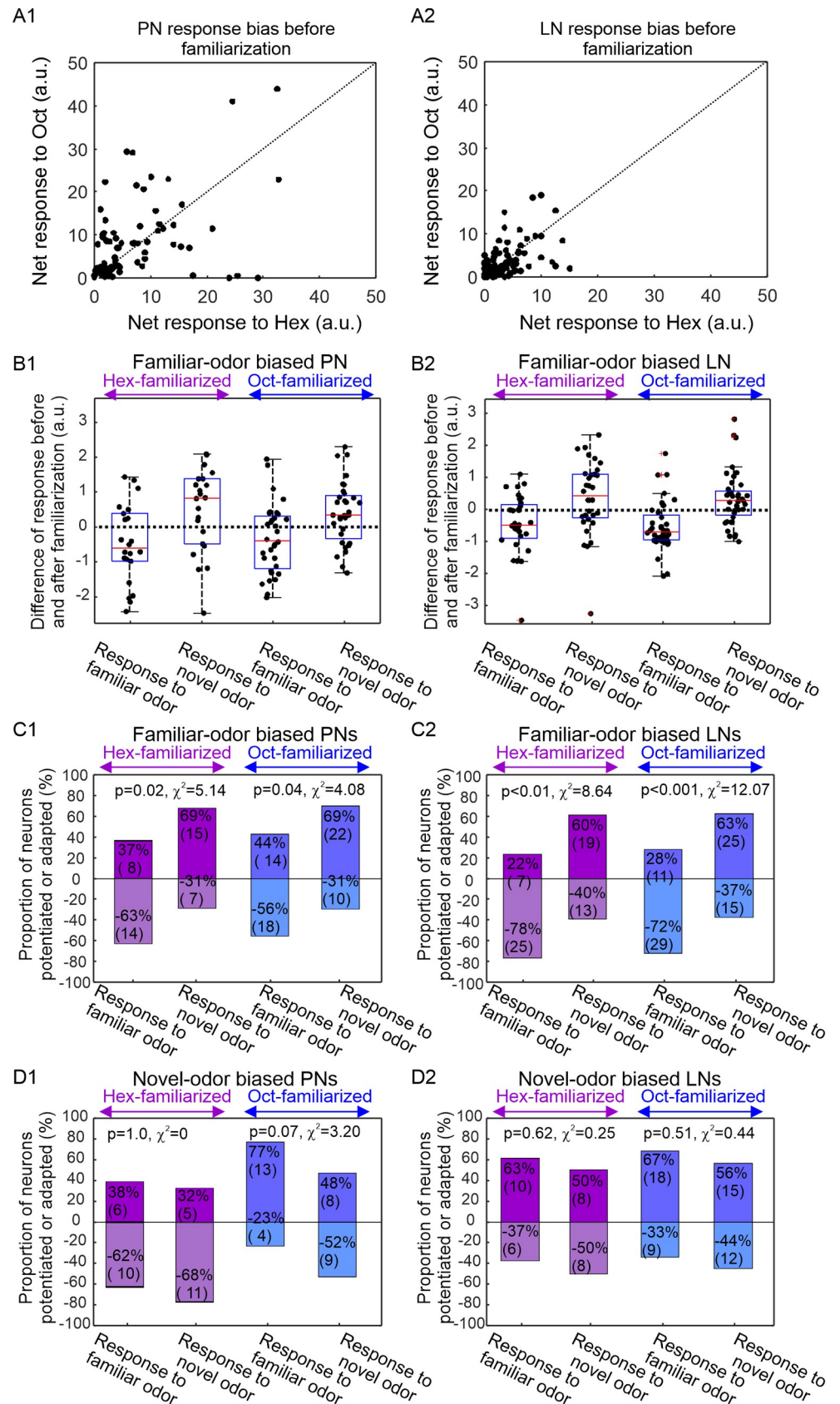
**Fig 4. Familiar-odor-biased PNs and LNs are novelty and familiarity detectors.** PNs and LNs display initial response biases to the two test odors Hex and Oct prior to familiarization (**A1, A2**). Some neurons respond more strongly to Oct than to Hex, i.e., data points above the diagonal line; some neurons respond more strongly to Hex than to Oct, i.e., data points below the diagonal line. Additionally, PNs are generally more responsive than LNs, evident from the wider distribution of data points along both X and Y axis. The Oct-biased units are above the diagonal line and the Hex-biased units are below the diagonal line. Then they are familiarized with Oct or Hex. Only the familiar-odor biased neurons showed consistent familiarity and novelty effects. In familiar-odor biased PNs (**B1**), whether it is Hex-familiarized or Oct-familiarized, most of the neurons decreased their responses to the familiar odor after the familiarization process, as revealed by the negative median values in the box plots (1st and 3rd boxes). In contrast, most of the neurons increased their responses to novel odor after the familiarization process–namely novelty effect, as shown by the positive median values in the box plots (2nd and 4th box). The familiarity and novelty effects are also evident in the familiar-odor biased LNs (**B2**). In Hex-familiarized familiar-odor biased PNs, 63% (n = 14) of the neurons exhibited the familiarity effect and 69% (n = 15) of the neurons exhibited the novelty effect; this distribution pattern is significantly different from random process (p = 0.02, McNemar test) (purple boxes, **C1**). In Oct-familiarized familiar-odor biased PNs, also seen were significantly higher percentage of neurons adapted by familiar odor (56%, n = 18) and potentiated by novel odor (69%, n = 22) (blue boxes, **C1**, p = 0.04, McNemar test). Similar phenomena were also observed among the familiar-odor biased LNs (**C2**). In novel-odor biased PNs and LNs, the familiar and novel odors did not produce contrasting changes after the familiarization process; none of the comparing pairs showed significant familiarity and novelty effects (**D1, D2**, McNemar test).

working memory to stimuli that may carry new information. Using antennal tracking we have developed a method for behaviorally identifying novelty detection in harnessed bees. We also found evidence of novelty detection in the primary olfactory neuropil, the AL. Overall, novelty detection in the AL appears to expressed in the subset of neurons biased to the familiar odor. Detection of novelty at this early processing stage could therefore enhance representation of novel stimuli in working memory.

## Antenna movement affected by familiar and novel odors

As a pair of prominent sensory organs, insect antennae move in specific ways upon stimulation. Cockroaches modify antenna movements in opposite ways in response to attractive and aversive odors [38]. Restrained honey bees move their antennae backwards to odor stimulation before conditioning, and then forward after odor has been conditioned to sucrose reward [30].
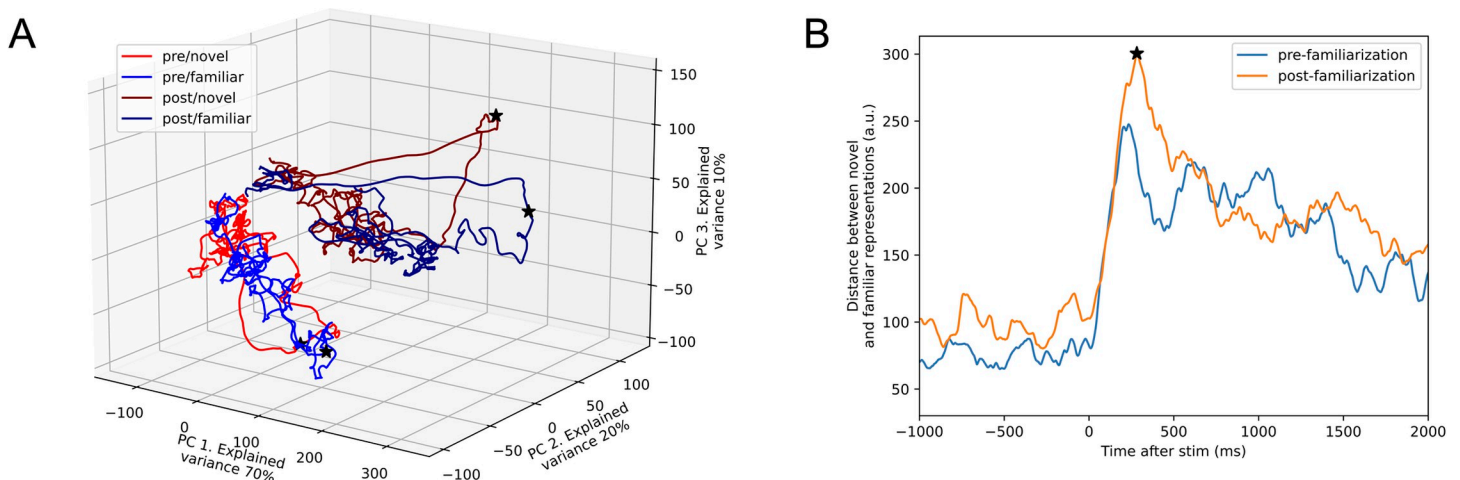


**Fig 5. Familiarization enlarges the differences between familiar- and novel-odor representations in AL.** (**A**) Principal components of firing rate of PN responses to familiar- and novel-odor before and after the familiarization process (pooled across hex-familiarized and oct-familiarized PNs). Black stars mark the time points where the peak response was. After familiarization, the novel odor evoked a response that showed distinct prominence at peak response relative to all other presentation types. (**B**) Familiarization produced increases in the distance between the novel and familiar PN response (pooled across hex-familiarized and oct-familiarized PNs). Black star occurs at the same time as in A. Stimulus onset was at 2s.

In our study we also found that honey bees hold their antennae at a backward position when stimulated by odor. We also show that this movement is modified after odors take on meaning. Specifically, that movement is attenuated after repeated exposure–familiarization–to an odor. In that context, when presented with a novel odor, the meaning of which is unknown, honey bees extend the time they hold the antenna in a backward position well beyond termination of the odor. All of this evidence suggests that antenna movements may reflect the meaning of odors. This is particularly clear when comparing pheromonal odors with floral odors. For example, honey bees show left-right asymmetry in antenna movement to the alarm pheromone, isoamyl acetate, but absence of asymmetry to the odors from floral sources [32]. In the context of our study, novelty can be interpreted as a feature that is induced by experience.

It is possible that this novelty response, and specific odor-driven movements of the antennae in general, affects sensing. After a bee has been conditioned to associate an odor with sucrose reinforcement, it responds to the odor by moving its antennae to the forward point where the bee has received sucrose-water droplets in the past [30]. Movements in this context could therefore enhance detection of both sucrose and odor in ways analogous to how bees move their antennae to inspect flowers [39]. On the other hand, bees may move their antennae in different ways upon stimulation with a novel or familiar odor, which in turn could change how the odor is perceived. That is, antennal movements described in our study could be considered as active sensing [40,41], meaning that movements mights enhance signal detection. Odor molecules are carried by turbulent airstreams that shear the clouds of molecules into thin filaments [42]. These filaments pass over the antenna for brief (milliseconds) periods. The movements we describe here could enhance detection of these sparse filaments, thus enhancing the detectability and/or discriminability of odors in an airstream. It could therefore be that the movements we describe here perform an analogous function to increased sniffing in mammals towards novel odors [41,43].

## Expanded coding dimensions for novelty and familiarity

The convergent anatomical relationship between glomeruli in the AL and receptors on antennae suggests that one main function of the AL is to encode the chemical identities of odor stimuli [37,44,45]. Odor molecules activate a range of receptor types depending on the molecular identities and binding properties of the receptors [46]. Axons projecting from the olfactory receptor neurons to the AL in turn activate their cognate glomeruli in the AL. The spatiotemporal activity patterns across glomeruli in the AL therefore reflects the response spectrum to different odors [37,47].

We have identified an important means for representing novelty and familiarity in the early olfactory processing circuits in the AL, which is overlaid on the glomerular map for odor identity. Our data suggest that glomeruli can participate in the encoding of familiarity and novelty by showing decreased responses to familiar odors and increased responses to novel odors (Fig 4). We observed the same response patterns irrespective of odor chemical identity, indicating that this phenomenon has the ability to encode a higher-dimensional feature (i.e. familiarity and novelty) in addition to the odor's chemical identity.

Plasticity at the LN-PN recurrent synapses could account for, at least in part, the familiarity/novelty effect [27]. In *D. melanogaster*, activation of PNs potentiates intraglomerular GABAergic LNs, which feedback to the PNs. Repeated stimulation of these PNs induces LNs to release more GABA, which in turn habituates PNs responses to the same stimulus via the GABA$_A$ receptors on the PN [48]. The observation of concurrent activation of both PN and LN within the same glomerulus led to a so called negative-image model wherein the inhibitory LNs construct a neural code that can counterbalance the mirror-imaged PN code over repeated stimulations, effectively reducing PN response to familiar odor [49].

Although PNs and LNs in every glomerulus can encode familiarity and novelty, the odors that can produce familiarity-associated reduction are most likely the odors that the glomerulus is tuned best to. This finding is consistent with a study of *D. melanogaster* in which the authors identified a glutaminergic mechanism underlying glomerulus-specific habituation [24]. Specifically, potentiated GABAergic LNs are necessary and sufficient to reduce PN responses to previously exposed odors. Moreover, these LNs co-release GABA and glutamate. The odor-specificity of habituation is achieved through the activation of NMDA receptors on the PNs. Our results, showing that PNs and LNs show reduced responses after the familiarization process to the odor that they are biased towards initially (Fig 4), is consistent with the odor-specific habituation model in *D. melanogaster*. Additionally, our study has also revealed that these biased PNs and LNs increase responses to a novel odor, which has not been reported elsewhere in studies of insect olfaction.

Although we have only tested one novel odor per animal, we predict for future study that other novel odors would produce a novelty effect. In other words, a sustained exposure to the odor that the glomerulus is most sensitive to creates a representation of familiarity by weakening responses to this odor; but the same glomerulus may generate a representation of novelty to many or all other non-selective odors. As such, the original glomerular output with a whole spectrum of responses evoked by a range of odors is re-organized to reflect previous experience—i.e. familiarization. After familiarization, the most effective odors become less effective and vice versa. Therefore, the adjusted contrast can represent familiarity and novelty. A strengthened response is associated with novel odor, and weakened response with familiar odor, irrespective of molecular identities. The code for familiarity and novelty could also contribute to odor categorization in AL [19]. All these ideas now need evaluation.

## Novelty encoding in AL and MB

The enhanced sensory patterns driven by novel odors should be integrated into higher order processing in the mushroom bodies and possibly also in the lateral protocerebrum [50–52]. Recently, a means for detecting novel odors was identified in the fruit fly mushroom bodies [25]. An identified dopaminergic neuron is responsible for the rapid transition from a familiar to a novel state in a group of mushroom body output neurons (MBONs). In that circuit, the novelty detection is not selective, meaning any new odor can release the MBONs from the suppressive state.

There are three hypothetical frameworks for placing our results in the context of the fruit fly results. First, novelty detection in the AL, which we propose here, could be a different mechanism from the dopaminergic mechanism in the mushroom bodies. The AL could augment the novelty coding in the mushroom body as the contrast between response to familiar and novel odors in the AL is projected to the mushroom body circuits. Second, novelty detection in the AL of the honey bee might not arise from properties intrinsic to the circuitry of the AL. Instead, the novelty effects we detected might have arisen in the MB and transmitted via feedback neurons to the AL. Such a circuit has been identified in the fruit fly [53] and in anatomical analyses of the honey bee brain [52]. Third, novelty detection in the honey bee may have been pushed from the MB to the AL because of important differences in the roles of different structures in the honey bee and fruit fly brains [54], just as species-specific differences affect homologous areas of mammalian brains [55]. The fruit fly mushroom bodies contain approximately 4,000 intrinsic neurons, and the brain itself contains approximately 135,000 neurons [56]. Thus, the mushroom bodies make up about 3% of the total brain neurons. Inputs to the fruit fly mushroom body are predominantly from the AL and carry olfactory information. In the honey bee, the mushroom bodies contain approximately 340,000 intrinsic

neurons, which comprises circa 34% of a brain with just under $10^6$ neurons [54]. The relatively larger size reflects the highly multimodal nature of the inputs from visual, mechanosensory, taste and olfactory processing centers in the honey bee brain [54]. Given the focus on multi-sensory information processing in the honey bee mushroom bodies, it could be that novelty detection has been pushed earlier in the sensory processing stream, into the AL, which would mean that the mechanisms we describe could be independent phylogenetic additions to olfactory processing in honey bees.

## Summary

We have described a process by which the honey bee AL distinguishes familiar- from novel-odors independent of their chemical identities. More work now needs to be done to determine how it is implemented, how long it persists, and how it functions in the natural environments of the honey bee. Our results, together with other studies of plasticity in the AL [19,27], expands the AL coding dimensions to include higher-order features such as olfactory familiarity and novelty. This new coding scheme in the AL, along with the novelty detection at higher synaptic centers such as MB, likely shift attention to novel odors, which may offer behavioral benefits to the animal when linked to active sensing [40,41].

## Materials and methods

### Animal preparation

Bees were prepared following a similar procedure described in Smith and Burden (2014) [28]. In short, non-pollen forager honey bees (*Apis mellifera* L.) were collected in the morning at the entrance of a hive maintained outdoor in natural lighting conditions, briefly cooled and restrained in individual harnesses. For behavioral experiments, bees were restrained with tape and a small amount of dental wax behind the head to fix their head in place. After recovering from cooling, bees were then fed 30% sucrose (w/w) until satiation and allowed to adjust to harnesses for approximately 1 hour in ambient conditions.

For electrophysiological experiments, bees were restrained in harnesses with dental wax around head. After recovering from cooling, bees were fed 2 μl of a 1.0 mol l$^{-1}$ sucrose solution and allowed to remain undisturbed for in a moisturized box until experiments took place. Before recording, the antennae were immobilized with eicosane gently applied to the base of scape and the joint between flagellum and pedicel. A rectangular window was cut open on the cuticle between the compound eyes to expose the antennal lobes. To minimize the muscular and hemolymph movement in the head capsule, the base of proboscis underneath the frontal cuticle plate was severed and the abdomen was removed. A continuous saline flow through the head capsule was supplied during the entire time course of recording.

### Electrophysiological recordings and experiment protocol

Extracellular recordings were performed in the left antennal lobe with a 16-channel probe (NeuroNexus, Ann Arbor, MI). Spike waveforms were digitized with a RZ2 system at a sampling rate of 20 KHz (Tucker-Davis Technologies, Alachua, FL). A total of 217 units from antennal lobes of 19 foragers was recorded. The experiment protocol follows previous publications with slight modifications [27]. Briefly, after a stable recording was achieved, the honey bee preparation was first stimulated with each of the following pure odors: hexanol (Hex), 2-octanone (Oct) (Sigma-Aldrich Chemie GmbH) and control (filter paper only). The duration of the pulse was 4 sec, and two minutes of recovery time were allowed between the two pulses. During the repeated exposure with Hex or Oct, 40 pulses were delivered with inter-

pulse interval of 60 sec, after which 10 min recovery was given before testing with the two odors again. The order of odor presentations was randomized during the entire protocol. These two odors are generic plant-derived volatiles with similar initial valence, evident from experiments where honey bees learned both odors equally well [57].

## Behavioral assays and familiarization protocol

Honey bees were placed under a constant humidified air flow and vacuum system, in order to remove excess odorants. Bees were recorded from above with a web camera at 30 frames per sec as described by Birgiolas et al. (2017) [29]. The experimental protocol follows that in the electrophysiological experiments with a few differences. In brief, the honey bees were first stimulated once for 4 seconds in a randomized order with hexanol, 2-octanone, and clean air. There was a 5 min recovery period between each of the odor stimulations. Next, the animals (N = 24) were put through a familiarization protocol in which they received 40 pulses of either Hex (N = 13) or Oct (N = 11) at an inter-pulse interval of 60 sec, after which 10 min recovery was given before testing with the odors again. To keep mechanical stimulation on antennae constant, a flowmeter (Cole-Parmer, IL) was used to ensure identical flow rate (35 mL/min) for odor delivery. The odor delivery tube was kept about 2 cm away from bee head across experiments.

## Analysis of spike data and video recordings

Extracellular spike waveforms are recorded with a TDT RZ2 system at 20 KHz sampling rate, then exported to Offline Sorter program (Plexon Inc, Dallas, TX) which classifies the similar waveforms into individual clusters (units) based on the relatedness of waveforms' projection onto a 3D space derived from the first three principal components that capture the most variation of the original waveforms. To increase the discriminating power, the original waveforms are grouped in a tetrode configuration [58,59], matching the physical design of the recording probe, i.e. 16 recording sites are distributed in two shanks in a block design of 2x4. Each block is called a tetrode. Statistical separation of waveform clusters, representing individual neurons or units, is aided with visual inspection, all implemented in the Offline Sorter program. Once satisfied with the clustering results, the time stamps of waveforms are then exported to Neuroexplorer program (Plexon Inc, Dallas, TX) and Matlab (Mathworks, Natick, MA) for further analysis.

Net response was calculated to quantify the stimulus triggered spike responses, using the following formula: net response = (post-stimulus response–pre-stimulus response)/pre-stimulus response. Here, the response is defined by the number of spikes within 1 or 4 sec duration after the onset of a response, which is about 0.15 sec after the opening of the solenoid valve indicated by a square pulse. After plotting out the peristimulus time histograms of all units to either Hex or Oct stimulus, it was clear that the responses have two distinct phases: transient phase and lasting phase (Fig 3F and 3G). The transient phase, lasting for about 1 sec, is present for all units; but the lasting phase is less consistent, and it can be as long as the stimulus duration (4 sec) or longer or shorter. For this reason, we focused our analysis on the more consistent transient phase despite that the stimulus duration was longer.

Behavioral videos were processed in SwarmSight [29] (swarmsight.org) in order to extract positions of antenna and proboscis and were exported to R (R Core Team 2017). Statistical analyses were used to compare the antennal movements of animals in three time-windows: 4 sec immediately before, 4 sec during, and 4 sec immediately after odor presentation. Custom code in R was used to calculate the mean antennal angles for each video recording when only clean humidified air was being presented to each bee. Then for each bee and each frame

included in our three time-windows (before, during, and after), a normalized angular difference from the mean antennal position was calculated. A two-way ANOVA and Tukey HSD post hoc analysis was then used to compare these normalized angular differences between neighboring time windows across animals before and after Latent Inhibition exposure to both the familiar and novel odors. We found no difference in response patterns dependent upon initial odor identity, and thus pooled odors based upon familiarity and not odor identity.

## Classification of putative PNs and LNs

We used cell-specific features to classify spike-sorted units into LNs and PNs. These features and the sorting protocol closely followed previous work [36] with one exception. We were unable to access certain cell properties (e.g., sub-threshold membrane potential) due to using extracellular recording methods. The features we used were as follows.

1. Change in firing rate. This was defined as the difference of the maximal firing rate after stimulus (within a 800ms-window) and the minimal firing rate in a 500ms pre-stimulus window. We calculated the firing rate following the method described in [36]. Briefly, for each unit, we first aligned different trials based on maximizing pairwise correlation of the time derivative [60]. We then averaged over trials and convolved this average with an asymmetric alpha kernel ($\alpha(t) = t \cdot \exp\left\{-\frac{t}{\tau}\right\}$, with $\tau$ = 8 ms).

2. Lag to response. This was calculated as the time between the stimulus onset and the first crossing of the half of the maximal median firing rate of response, calculated over the response window.

3. Variability in the inter-spike interval. Following [36], we used a modified coefficient of variation, CV2. This metric was introduced to quantify interval dispersion when the firing rate of a cell is modulated [61]. It is defined as the variance of two consecutive inter-spike intervals divided by their mean. We then averaged this metric over all spike pairs and all trials.

4. Variability across trials. This was calculated as the Fano factor, i.e. ratio of variance to mean, of the number of spikes in the response window (800 ms) across different trials.

These four features were then used in a hierarchical clustering analysis using the Ward linkage method and the Euclidean distance metric (calculations were carried out with scipy's *linkage* and *fcluster* functions). These features provided two well-defined clusters of distinct cell types. Projection neurons were defined by those that had larger change in firing rate due to response. Our sorted cells occupied similar regions in reduced space as the sorted data from intracellularly recorded PNs and LNs [36] (Fig 2).

To minimize the possible effect of familiarization on spiking patterns, we only selected the subset of data in the first half of the familiarization process (i.e., first 20/40 trials) for the purpose of cell type classification.

## Supporting information

**S1 Fig. Right antenna movement to novel and familiar odors.** Angular positions are defined as in Fig 1. **A**. The average distribution densities of right antennae's angular positions in response to odors before the familiarization process (left column plots) and 10 min after the familiarization process (right column plots) aligned by odor onset over 12 s Statistical analyses: Two-way ANOVA, difference measure~ time period * odor, df = 2, n = 24, Tukey HSD post-hoc comparison, asterisks indicate statistical significance, **** p<0.00001, ns indicates not significant. (TIF)

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## Author Contributions

**Conceptualization:** Hong Lei, Maxim Bazhenov, Brian H. Smith.

**Data curation:** Hong Lei, Seth Haney, Christopher M. Jernigan.

**Formal analysis:** Hong Lei, Seth Haney, Christopher M. Jernigan.

**Funding acquisition:** Maxim Bazhenov, Brian H. Smith.

**Investigation:** Hong Lei.

**Methodology:** Hong Lei, Xiaojiao Guo, Chelsea N. Cook.

**Project administration:** Brian H. Smith.

**Resources:** Brian H. Smith.

**Software:** Hong Lei, Seth Haney, Christopher M. Jernigan.

**Supervision:** Brian H. Smith.

**Writing – original draft:** Hong Lei.

**Writing – review & editing:** Hong Lei, Seth Haney, Christopher M. Jernigan, Xiaojiao Guo, Chelsea N. Cook, Maxim Bazhenov, Brian H. Smith.

## References

1. Kent CB, Aldridge JW. Special review: decision utility, the brain, and pursuit of hedonic goals. Social Cognition. 2008; 26(5):621–46. https://doi.org/10.1521/soco.2008.26.5.621 PMID: 20198128

2. Grabenhorst F, Rolls ET, Margot C, da Silva MA, Velazco MI. How pleasant and unpleasant stimuli combine in different brain regions: odor mixtures. The Journal of neuroscience: the official journal of the Society for Neuroscience. 2007; 27(49):13532–40. https://doi.org/10.1523/JNEUROSCI.3337-07.2007 PMID: 18057211.

3. Baddeley AD, Hitch G. Working memory. In: Bower GH, editor. Psychology of learning and motivation. 8: Academic Press; 1974. p. 47–89.

4. Lewis-Peacock JA, Kessler Y, Oberauer K. The removal of information from working memory. Annals of the New York Academy of Sciences. 2018; 1424(1):33–44. https://doi.org/10.1111/nyas.13714 PMID: 29741212

5. Conway ARA, Jarrold C, Kane MJ. Variation in working memory. Cary: Cary: Oxford University Press; 2006.

6. Oberauer K. Removal of irrelevant information from working memory: sometimes fast, sometimes slow, and sometimes not at all. Annals of the New York Academy of Sciences. 2018; 1424(1):239–55. https://doi.org/10.1111/nyas.13603 PMID: 29532484

7. Treviño M, Aguilar-Garnica E, Jendritza P, Li S-B, Oviedo T, Köhr G, et al. Discrimination learning with variable stimulus 'salience'. International Archives of Medicine. 2011;4:26-. https://doi.org/10.1186/1755-7682-4-4 PubMed PMID: PMC3176477. PMID: 21255404

8. Mackintosh NJ. A theory of attention: a variations in the associability of stimuli with reinforcement. Psychological Review. 1975; 82(4):276. https://doi.org/10.1002/cncr.11576 PMID: 1291050844.

9. Chandra SBC, Hosler JS, Smith BH. Heritable variation for latent inhibition and its correlation with reversal learning in honeybees *Apis mellifera*. Journal of Comparative Psychology. 2000; 114(1):86–97. https://doi.org/10.1037/0735-7036.114.1.86 PMID: 10739314

10. Chandra SBC, Wright GA, Smith BH. Latent inhibition in the honey bee, *Apis mellifera*: Is it a unitary phenomenon? Animal Cognition. 2010; 13(6):805–15. https://doi.org/10.1007/s10071-010-0329-6 PMID: 20521073

11. Lubow RE, Moore AU. Latent inhibition: The effect of nonreinforced pre-exposure to the conditional stimulus. Journal of Comparative and Physiological Psychology. 1959; 52(4):415–9. https://doi.org/10.1037/h0046700 PMID: 14418647

12. Johnson B, Woo C, ingco E, ham K, eon M. Multidimensional chemotopic responses to n-aliphatic acid odorants in the rat olfactory bulb. Journal of Comparative Neurology. 1999; 409(4):529–48. PMID: 10376738

13. Ma L, Qiu Q, Gradwohl S, Scott A, Yu EQ, Alexander R, et al. Distributed representation of chemical features and tunotopic organization of glomeruli in the mouse olfactory bulb. Proceedings of the National Academy of Sciences of the United States of America. 2012; 109(14):5481–6. https://doi.org/10.1073/pnas.1117491109 PMID: 22431605

14. Chen J-Y, Marachlian E, Assisi C, Huerta R, Smith BH, Locatelli F, et al. Learning modifies odor mixture processing to improve detection of relevant components. The Journal of neuroscience: the official journal of the Society for Neuroscience. 2015; 35(1):179–97. https://doi.org/10.1523/JNEUROSCI.2345-14.2015 PubMed PMID: PMC4287141. PMID: 25568113

15. Fernandez PC, Locatelli FF, Person-Rennell N, Deleo G, Smith BH. Associative conditioning tunes transient dynamics of early olfactory processing. The Journal of neuroscience: the official journal of the Society for Neuroscience. 2009; 29(33):10191–202.

16. Hammer M, Menzel R. Learning and memory in the honeybee. The Journal of neuroscience: the official journal of the Society for Neuroscience. 1995; 15(3):1617–30.

17. Riffell JA, Lei H, Abrell L, Hildebrand JG. Neural basis of a pollinator's buffet: olfactory specialization and learning in *Manduca sexta*. Science. 2013; 339(6116):200–4. https://doi.org/10.1126/science.1225483 PMID: 23223454.

18. Bazhenov M, Stopfer M, Sejnowski TJ, Laurent G. Fast odor learning improves reliability of odor responses in the locust antennal lobe. Neuron. 2005; 46(3):483–92. https://doi.org/10.1016/j.neuron.2005.03.022 PMID: 15882647

19. Locatelli FF, Fernandez PC, Smith BH. Learning about natural variation of odor mixtures enhances categorization in early olfactory processing. Journal of Experimental Biology. 2016; 219(17):2752. https://doi.org/10.1242/jeb.141465 PMID: 27412003

20. Matsumoto Y, Mizunami M. Olfactory memory capacity of the cricket *Gryllus bimaculatus*. Biology Letters. 2006; 2(4):608–10. https://doi.org/10.1098/rsbl.2006.0540 PubMed PMID: PMC1834001. PMID: 17148301

21. Lovelace CT, Slotnick BM. Memory for brief, widely spaced odor presentations in the rat. Chemical Senses. 1995; 20(2):183–90. https://doi.org/10.1093/chemse/20.2.183 PMID: 7583010

22. Hammer M. An identified neuron mediates the unconditioned stimulus in associative olfactory learning in honeybees. Nature. 1993; 366(6450):59–63. https://doi.org/10.1038/366059a0 PMID: 24308080

23. Farooqui T, Robinson K, Vaessin H, Smith BH. Modulation of early olfactory processing by an ocotpaminergic reinforcement pathway in the honeybee. The Journal of neuroscience: the official journal of the Society for Neuroscience. 2003; 23(12):5370–80.

24. Das S, Sadanandappa MK, Dervan A, Larkin A, Lee JA, Sudhakaran IP, et al. Plasticity of local GABAergic interneurons drives olfactory habituation. Proceedings of the National Academy of Sciences. 2011; 108(36):E646–E54. https://doi.org/10.1073/pnas.1106411108 PMID: 21795607

25. Hattori D, Aso Y, Swartz KJ, Rubin GM, Abbott LF, Axel R. Representations of novelty and familiarity in a mushroom body compartment. Cell. 2017; 169(5):956–69.e17. https://doi.org/10.1016/j.cell.2017.04.028 PMID: 28502772

26. Li F, Lindsey JW, Marin EC, Otto N, Dreher M, Dempsey G, et al. The connectome of the adult Drosophila mushroom body provides insights into function. eLife. 2020; 9:e62576. https://doi.org/10.7554/eLife.62576 PMID: 33315010

27. Locatelli FF, Fernandez PC, Villareal F, Muezzinoglu K, Huerta R, Galizia CG, et al. Nonassociative plasticity alters competitive interactions among mixture components in early olfactory processing. European Journal of Neuroscience. 2013; 37(1):63–79. https://doi.org/10.1111/ejn.12021 PMID: 23167675

28. Smith BH, Burden CM. A proboscis extension response protocol for investigating behavioral plasticity in insects: application to basic, biomedical, and agricultural research. Journal of Visualized Experiments. 2014;(91):51057. https://doi.org/10.3791/51057 PMID: PMC4828057.

29. Birgiolas J, Jernigan CM, Gerkin RC, Smith BH, Crook SM. SwarmSight: real-time tracking of insect antenna movements and proboscis extension reflex using a common preparation and conventional hardware. JoVE. 2017. https://doi.org/10.3791/56803 PMID: 29364251

30. Cholé H, Junca P, Sandoz J-C. Appetitive but not aversive olfactory conditioning modifies antennal movements in honeybees. Learning & Memory. 2015; 22(12):604–16. https://doi.org/10.1101/lm.038448.115 PubMed PMID: PMC4749730. PMID: 26572651

31. Kisch J, Erber J. Operant conditioning of antennal movements in the honey bee. Behavioural Brain Research. 1999; 99(1):93–102. https://doi.org/10.1016/S0166-4328(98)00076-X PMID: 10512576

32. Rogers LJ, Vallortigara G. Complementary Specializations of the Left and Right Sides of the Honeybee Brain. Frontiers in Psychology. 2019;10. https://doi.org/10.3389/fpsyg.2019.00010 PMID: 30740069

33. McAfee A, Collins TF, Madilao LL, Foster LJ. Odorant cues linked to social immunity induce lateralized antenna stimulation in honey bees (Apis mellifera L.). Scientific Reports. 2017; 7(1):46171. https://doi.org/10.1038/srep46171 PMID: 28387332

34. Mondet F, Blanchard S, Barthes N, Beslay D, Bordier C, Costagliola G, et al. Chemical detection triggers honey bee defense against a destructive parasitic threat. Nature Chemical Biology. 2021; 17 (5):524–30. https://doi.org/10.1038/s41589-020-00720-3 PMID: 33495646

35. Martin JP, Beyerlein A, Dacks AM, Reisenman CE, Riffell JA, Lei H, et al. The neurobiology of insect olfaction: sensory processing in a comparative context. Progress in Neurobiology. 2011; 95(3):427–47. https://doi.org/10.1016/j.pneurobio.2011.09.007 PMID: 21963552

36. Meyer A, Galizia CG, Nawrot MP. Local interneurons and projection neurons in the antennal lobe from a spiking point of view. Journal of Neurophysiology. 2013; 110(10):2465–74. https://doi.org/10.1152/jn.00260.2013 PMID: 24004530

37. Sachse S, Rappert A, Galizia CG. The spatial representation of chemical structures in the antennal lobe of honeybees: steps towards the olfactory code. European Journal of Neuroscience. 1999; 11:3970–82. https://doi.org/10.1046/j.1460-9568.1999.00826.x PMID: 10583486

38. Nishiyama K, Okada J, Toh Y. Antennal and locomotor responses to attractive and aversive odors in the searching cockroach. Journal of Comparative Physiology A. 2007; 193(9):963–71. https://doi.org/10.1007/s00359-007-0249-3 PMID: 17609964

39. Kevan PG, Lane MA. Flower petal microtexture is a tactile cue for bees. Proceedings of the National Academy of Sciences of the United States of America. 1985; 82(14):4750–2. https://doi.org/10.1073/pnas.82.14.4750 PMID: 16593582.

40. Huston SJ, Stopfer M, Cassenaer S, Aldworth Zane N, Laurent G. Neural Encoding of Odors during Active Sampling and in Turbulent Plumes. Neuron. 2015; 88(2):403–18. https://doi.org/10.1016/j.neuron.2015.09.007 PMID: 26456047

41. Crimaldi JP, Smith BH, Schaefer A, Schmuker M, True AC, Verhagen JV, et al. Acitve sensing in a dynamic olfactory world. Journal of Computational Neuroscience. 2021;(accepted). https://doi.org/10.1007/s10827-021-00798-1 PMID: 34591220

42. Connor EG, McHugh MK, Crimaldi JP. Quantification of airborne odor plumes using planar laser-induced fluorescence. Experiments in Fluids. 2018; 59(9):137. https://doi.org/10.1007/s00348-018-2591-3

43. Arbuckle EP, Smith GD, Gomez MC, Lugo JN. Testing for odor discrimination and habituation in mice. Journal of visualized experiments: JoVE. 2015;(99):e52615. Epub 2015/05/21. https://doi.org/10.3791/52615 PMID: 25992586; PubMed Central PMCID: PMC4542325.

44. Jefferis GS, Potter CJ, Chan AM, Marin EC, Rohlfing T, Maurer CR Jr., et al. Comprehensive maps of Drosophila higher olfactory centers: spatially segregated fruit and pheromone representation. Cell. 2007; 128(6):1187–203. https://doi.org/10.1016/j.cell.2007.01.040 PMID: 17382886; PubMed Central PMCID: PMC1885945.

45. Johnson BA, Ho SL, Xu Z, Yihan JS, Yip S, Hingco EE, et al. Functional mapping of the rat olfactory bulb using diverse odorants reveals modular responses to functional groups and hydrocarbon structural features. Journal of Comparative Neurology. 2004; 449:180–94.

46. Hallem EA, Carlson JR. Coding of odors by a receptor repertoire. Cell. 2006; 125(1):143–60. https://doi.org/10.1016/j.cell.2006.01.050 PMID: 16615896.

47. Deisig N, Giurfa M, Lachnit H, Sandoz JC. Neural representation of olfactory mixtures in the honeybee antennal lobe. European Journal of Neuroscience. 2006; 24(4):1161–74. https://doi.org/10.1111/j.1460-9568.2006.04959.x PMID: 16930442

48. Sudhakaran IP, Holohan EE, Osman S, Rodrigues V, VijayRaghavan K, Ramaswami M. Plasticity of Recurrent Inhibition in the Drosophila Antennal Lobe. The Journal of Neuroscience. 2012; 32 (21):7225–31. https://doi.org/10.1523/JNEUROSCI.1099-12.2012 PMID: 22623667

49. Ramaswami M. Network Plasticity in Adaptive Filtering and Behavioral Habituation. Neuron. 2014; 82 (6):1216–29. https://doi.org/10.1016/j.neuron.2014.04.035 PMID: 24945768

50. Bernd G. Morphology of feedback neurons in the mushroom body of the honeybee, Apis mellifera. Journal of Comparative Neurology. 1999; 404(1):114–26. https://doi.org/10.1002/(SICI)1096-9861(19990201)404:1<114::AID-CNE9>3.0.CO;2-#

51. Strausfeld NJ. Organization of the honey bee mushroom body: representation of the calyx within the vertical and gamma lobes. Journal of Comparative Neurology. 2002; 450(1):4–33. https://doi.org/10.1002/cne.10285 PMID: 12124764

**52.** Rybak J, Menzel R. Anatomy of the mushroom bodies in the honey bee brain: The neuronal connections of the alpha-lobe. Journal of Comparative Neurology. 1993; 334(3):444–65. https://doi.org/10.1002/cne.903340309 PMID: 8376627

**53.** Hu A, Zhang W, Wang Z. Functional feedback from mushroom bodies to antennal lobes in the Drosophila olfactory pathway. Proceedings of the National Academy of Sciences. 2010; 107(22):10262–7. https://doi.org/10.1073/pnas.0914912107 PMID: 20479249

**54.** Heisenberg M. What do the mushroom bodies do for the insect brain? an introduction. Learning & Memory. 1998; 5(1–2):1–10. PMID: 10454369.

**55.** Hodge RD, Bakken TE, Miller JA, Smith KA, Barkan ER, Graybuck LT, et al. Conserved cell types with divergent features in human versus mouse cortex. Nature. 2019; 573:61–8. https://doi.org/10.1038/s41586-019-1506-7 PMID: 31435019

**56.** Zheng Z, Lauritzen JS, Perlman E, Robinson CG, Nichols M, Milkie D, et al. A complete electron microscopy volume of the brain of adult *Drosophila melanogaster*. Cell. 2018; 174(3):730-43.e22. https://doi.org/10.1016/j.cell.2018.06.019 PMID: 30033368

**57.** Wright GA, Thomson MGA, Smith BH. Odour concentration affects odour identity in honeybees. Proceedings of the Royal Society B: Biological Sciences. 2005; 272(1579):2417–22. https://doi.org/10.1098/rspb.2005.3252 PMID: 16243694

**58.** Gray CM, Maldonado PE, Wilson M, McNaughton B. Tetrodes markedly improve the reliability and yield of multiple single-unit isolation from multi-unit recordings in cat striate cortex. Journal of Neuroscience Methods. 1995; 63(1):43–54. https://doi.org/10.1016/0165-0270(95)00085-2 PMID: 8788047

**59.** Lei H, Christensen TA, Hildebrand JG. Spatial and temporal organization of ensemble representations for different odor classes in the moth antennal lobe. The Journal of neuroscience: the official journal of the Society for Neuroscience. 2004; 24:11108–19. https://doi.org/10.1523/JNEUROSCI.3677-04.2004 PMID: 15590927

**60.** Nawrot MP, Aertsen A, Rotter S. Elimination of response latency variability in neuronal spike trains. Biological Cybernetics. 2003; 88(5):321–34. https://doi.org/10.1007/s00422-002-0391-5 PMID: 12750895

**61.** Nawrot MP. Analysis and Interpretation of Interval and Count Variability in Neural Spike Trains. In: Grün S, Rotter S, editors. Analysis of Parallel Spike Trains. Springer Series in Computational Neuroscience. Boston, MA: Springer US; 2010. p. 37–58.