Bumblebee mouthparts exhibit poor acuity for the detection of pesticides in nectar

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Abstract (max 200 words)

Bees are important pollinators of agricultural crops, but their populations are at risk when pesticides are used. One of the largest risks bees face is poisoning of floral nectar and pollen by insecticides. Studies of bee detection of neonicotinoids have reported contradictory evidence about whether bees can taste these pesticides in sucrose solutions and hence avoid them. Here, we use an assay for the detection of food aversion combined with single-sensillum electrophysiology to test whether the mouthparts of the buff-tailed bumblebee (*Bombus terrestris*) detect the presence of pesticides in a solution that mimicked the nectar of oilseed rape (*Brassica napus*). Bees did not avoid consuming solutions containing concentrations of imidacloprid, thiamethoxam, clothianidin, or sulfoxaflor spanning six orders of magnitude, even when these solutions contained lethal doses. Only extremely high concentrations of the pesticides altered spiking in gustatory neurons through a slight reduction in firing rate or change in the rate of adaptation. These data provide strong evidence that bumblebees cannot detect or avoid field-relevant concentrations of pesticides using information from their mouthparts. As bees rarely contact floral nectar with other body parts, we predict

that they are at high risk of unwittingly consuming pesticides in the nectar of pesticide-treated crops.

Keywords: Neonicotinoids, sulfoxaflor, bumblebees, oil seed rape, taste perception

Main text

Insect pollination is a critical ecosystem service. The most economically valuable pollinators are bees (Calderone, 2012; Garibaldi et al., 2014; Huang and An, 2018), especially domesticated bees that secure crop yield and quality (Meehan et al., 2011). In agricultural ecosystems, however, insecticides are widely used to protect crop yields (Klein et al., 2007). Using insecticides impacts the health and survival of bees, contributing to the recent population declines of all bee species (Goulson et al., 2015; Potts et al., 2016; van der Sluijs et al., 2013; Vanbergen et al., 2013). Hundreds of studies have shown that exposure to sublethal concentrations of neonicotinoid pesticides (i.e. imidacloprid, IMD, thiamethoxam, TMX, and clothianidin, CLO) in food impairs foraging behaviour, homing and orientation behaviour, and olfactory learning and memory (e.g., Gill et al., 2012; Henry et al., 2012; Parkinson et al., 2022a; Schneider et al., 2012a; Williamson et al., 2014; Wright et al., 2015). Most studies administer pesticides in sugar solutions; bees consume the solution, and then a change in behaviour or performance is recorded. If bees could detect and avoid pesticides in food, however, these substances could be used to defend crops against pests without risk to bees. Only a few have explicitly tested whether bees can detect and avoid neonicotinoid pesticides in nectar (Arce et al., 2018; Kessler et al., 2015; Muth et al., 2020), but the conclusions of these studies are contradictory.

We previously found that when bees are given a choice between sucrose solution and sucrose containing field-relevant doses of IMD and TMX, bees choose the neonicotinoid solution (Kessler et al., 2015). This could indicate that bees find neonicotinoid pesticides phagostimulatory. However, we explicitly tested if bees could detect IMD, TMX, or CLO in water and in sucrose solution by recording from the gustatory receptor neurons (GRNs) of the galeal sensilla of the bees' mouthparts (Kessler et al., 2015). We failed to

find a change in the rate of GRN spiking that indicated detection and deduced that these compounds were not detected by bees using their sense of taste. This conclusion, however, has been challenged by a study in free-flying *B. terrestris* foragers (Arce et al., 2018). They also found that free-flying bumblebees preferred specific concentrations of solutions laced with TMX (Arce et al., 2018). In this study, the location of the solutions was randomized, forcing a choice at the point of feeding. These authors concluded that the only way bees could solve this problem was if they used their sense of taste to identify the preferred solution, arguing that further work needed to be done to identify the mechanism for sensation. Subsequently, however, another study in a different species of bumblebees (*B. impatiens*) using methods similar to ours reported that bees are neither attracted nor deterred from consuming sugar solutions containing neonicotinoids, consistent with the idea that they cannot detect the pesticides (Muth et al., 2020). Thus, whether or not bumblebees can detect neonicotinoids in food using their sense of taste remains unresolved.

Insects detect potential toxins using GRNs located in contact chemosensilla on their mouthparts, antennae, and tarsi using two mechanisms: active spiking of GRNs expressing receptors tuned to bitter substances (Weiss et al., 2011) or via the inactivation of sugar-sensing GRNs (French et al., 2015). In our previous work (Kessler et al., 2015), stimulation of the mouthpart galeal sensilla with neonicotinoids did not elicit spikes in putative bitter sensing GRNs. We also did not observe reduction in the rate of firing of the GRNs in the sensilla. However, we have since developed more advanced methods of spike sorting and data analysis that made it possible to discover that bumblebees have highly specialized mechanisms for encoding sugars. In bumblebee galeal sensilla, stimulation with sugars produces coherent spiking in 2 GRNs which burst in response to stimulation with high-value saccharide compounds (Miriyala et al., 2018; Parkinson et al., 2022b). We discovered that bumblebees also highly value the monosaccharide, fructose, and have a GRN tuned to detect it (Parkinson et al., 2022b). It is possible that changes to the burst pattern of firing could indicate that the presence of a compound such as a neonicotinoid in food. Furthermore, the type of sugar used to stimulate the sensilla could also influence whether pesticides

were detected in food (Parkinson et al., 2022b). We also know that the labial palps, a section of the mouthparts critical to toxin detection in other insect species (Chapman and Sword, 1993), could house additional GRNs sensitive to bitter compounds like pesticides. Our previous work used sucrose to stimulate the galeal sensilla and did not analyse how pesticides might alter the burst structure of the galeal GRN response to sugars or test the labial palps. Clearly, deeper investigations could determine whether the mouthparts GRNs possess novel gustatory mechanisms for pesticide detection and provide critical information about the risk to bees of consuming the nectar of pesticide-defended crops in the field.

Here, we use a combination of sensitive behavioural assays and electrophysiology to test in detail whether bumblebee mouthparts have mechanisms to detect pesticides in nectar. Feeding assays using freely moving foragers make it possible to assess if bees detect and avoid potential toxins in food (Ma et al., 2016). To definitively test whether bumblebees detect neonicotinoids on their mouthparts, we quantified the structure of feeding when the mouthparts of freely-moving bumblebees (*B. terrestris)* were stimulated with nectar-like solutions containing pesticides over a 2 min period (Ma et al., 2016). We specifically tested a mixture of primarily fructose and glucose that mimicked the nectar of oilseed rape (*Brassica napus*) with field-relevant concentrations of neonicotinoids. In addition, we comprehensively tested these solutions on the gustatory receptor neurons in the A-type sensilla on the galea and the labial palps of the bees' mouthparts using electrophysiology to determine whether sensilla in multiple locations are able to detect neonicotinoids (IMD, CLO, and TMX) and the sulfoxamine pesticide, sulfoxaflor (SFX). The burst-spiking of the galeal GRNs was analysed for changes to structure and compared to the GRN response to the bitter compound, quinine (QUI), which has been reported previously to be a feeding deterrent to bees (Ma et al., 2016; Wright et al., 2010).

Methods

Bumblebee colonies

Bumblebee colonies (*Bombus terrestris audax,* Biobest, Westerlo, Belgium*)* were maintained at laboratory conditions (22-27°C and 35-40% RH) at the University of Oxford and fed *ad libitum* with the proprietary sugar syrup provided with the colonies (BioGluc®, Biobest, Westerlo, Belgium) containing fructose (37.5%), glucose (34.5%), sucrose (25%), maltose (2%), oligosaccharides (1%), and the preservatives potassium sorbate (E202) 0.15% and citric acid (E330) 0.06% (Wäckers et al., 2017). Bumblebees were provided with freeze-dried honeybee collected pollen (approx. 10 g) (Agralan Growers, Wiltshire, UK) three times/week.

In total, 12 colonies were used for the taste assays and 6 colonies were used for the electrophysiological study. Bees were randomly assigned to a treatment and colonies were counterbalanced across treatments to control for intercolony variation.

Solutions

An artificial oilseed rape nectar sugar solution was created containing 1.04 M glucose (D-(+)-Glucose, Sigma Aldrich), 0.746 M fructose (D-(-)-Fructose, Sigma Aldrich), and 0.007 M sucrose (Sigma Aldrich) (Carruthers et al., 2017), hereafter referred to as ‘OSR’.

Stock solutions (1 mM) were made for each pesticide in OSR solution. No solvents are needed at these concentrations as all pesticides used are readily soluble in water at concentrations far exceeding 1 mM. Concentrations of imidacloprid (IMD), thiamethoxam (TMX), and clothianidin (CLO) in floral nectar range from 1.3 to 64 nM (Wood and Goulson, 2017), and sulfoxaflor (SFX) can reach concentrations as high as 71.4 µM (U.S. Environmental Protection Agency (EPA), 2014). In order to assess field-relevant concentrations of each chemical, a concentration series of each of IMD, TMX, CLO (Sigma Aldrich) and SFX (Chem Service) was made via tenfold serial dilution

using OSR to produce nectar containing the pesticides at 1000, 100, 10, and 1, and 0 nM (pure OSR). Additionally, 0.1 mM of each chemical dissolved in OSR was assessed alongside 0.1 mM and 1.0 mM QUI ((-)-Quinine hydrochloride dihydrate, Sigma Aldrich) in OSR, which functioned as positive controls for the effects of a bitter tastant. A concentration of 0.1 mM was chosen for the pesticides as this encompasses the higher range of SFX found in nectar, and allowed us to see if extremely high concentrations of IMD, TMX and CLO could be detected by bees.

Aversive taste assay

Bumblebee workers were collected directly from the colony under red light and placed individually into plastic holding vials with ventilation holes drilled into the lid. To minimise inclusion of nest bees (i.e. bees that never or rarely forage), only workers with a thorax width > 4.0 mm were used in these experiments (Goulson et al., 2002). In order to motivate the bees to feed during the assay, bees were deprived of food between 3-6 h. Bees were held in individual plastic holding vials at laboratory conditions in total darkness throughout the starvation period. Following the starvation period, individual bees were transferred into a 15 ml falcon tube, modified such that the tip of the tube was removed and a small (10 mm x 20 mm) steel mesh was affixed contiguous with the resulting hole. Bees could extend their proboscis through this hole to reach the feeding solutions, whilst the mesh served as a surface for the bees to grip onto to maintain their position during feeding. The tube was then affixed to a polystyrene holder with dental wax (Ma et al., 2016).

A 60 mm long, 100 µL glass capillary tube was filled with a test solution and scanned onto a computer at 600 dpi to produce an image from which the start volume could be measured. The capillary tube was then connected to a silicone tube which was in turn connected to a 1.0 ml syringe via a female connector, as in (Ma et al., 2016). This syringe functioned as a pipette bulb to maintain the feeding solution at the tip of the microcapillary. The capillary was held in place in the apparatus via a 1.0 ml modified syringe affixed to a micromanipulator. A DinoLite digital microscope camera (Model

AM4815ZT, DinoLite, The Netherlands) was positioned 20 cm above the feeding site where the bees accessed the test solutions. This was connected to a computer and set to record using DinoLite Digital Microscope software (DinoLite, The Netherlands) at a frame rate of 640 X 480 at 25X magnification. All feeding behaviour was recorded for later analysis.

Once a bee was positioned in the apparatus, they were given 3 min to habituate to their environment before the assay began. Following this, bees were encouraged to extend their proboscis by touching the bee's terminal antennomers with a droplet (~3.5 µL) of 0.5 M sucrose (Sigma Aldrich) dissolved in deionised water. Once the bee extended their proboscis, the droplet was presented to the bees' mouthparts for them to consume. Each bee was given up to 5 min to extend their proboscis and consume the droplet. Bees that did not do so were removed from the experiment. When the bee finished consuming the droplet, the microcapillary tube containing the test solution was presented to the bees extended mouthparts. The test phase began once the bee's proboscis contacted the test solution, and the bee was given 2 min to consume the solution. After feeding, microcapillaries were re-scanned to measure the end volume.

All experimenters were blind to the experimental treatments. All solutions were tested in a randomised order and treatments were counterbalanced over time to eliminate any effects of starvation time on feeding behaviour.

Measuring solution consumption and feeding behaviour

ImageJ (Schneider et al., 2012b) was used to produce measurements of the length of solution in each microcapillary before and after the assay. The reference scale was set to 60.0 mm. Image files were zoomed in to 400% and the length of the solution inside the microcapillary was measured meniscus to meniscus. The length of test solution consumed by each bee was calculated as the difference between the measured length of the liquid inside the microcapillary tube before and after the test phase. These lengths were then converted to volumes using the formula:

$$(100\ \mu L \times X\ mm) / 60.0\ mm$$

Where 100 µL is the maximum volume of the capillary tube, 60.0 mm is the length of the capillary tube, and X mm is the amount of solution consumed as a measured length within the capillary.

A feeding bout is defined as a period in which contact is made between the proboscis and test solution that is not separated by an absence of contacts for 5 s or more. The number of feeding bouts and their duration can be used to evaluate the phagostimulatory or deterrent activity of the compounds tested (Ma et al., 2016). To identify bouts of feeding behaviour, videos were played back at 50 % speed and periods of contact between the bees' mouthparts and the solution were scored using the Noldus Observer (Noldus, the Netherlands).

Electrophysiology

We performed extracellular tip recordings on individual taste sensilla on the bumblebee mouthparts to assess the peripheral taste perception of sucrose, a 10% dilution of oilseed rape nectar (10% OSR), and the addition of pesticides or QUI to 10% OSR. We recorded from 'A-type' sensilla from the galea (Gal), which are known to produce bursting spike trains in response to sugars (Miriyala et al., 2018) and the third and fourth segments of the labial palps (LP_{III} and LP_{IV}, respectively, Figure 1 A). Bumblebees were prepared for electrophysiology as described previously (Miriyala et al., 2018; Parkinson et al., 2022b). Sensilla were stimulated for 5 s with a borosilicate (Clark capillary glass 30-066, GC150TF-10) recording electrode (20 µm tip diameter, made with a Narishige PC-10 electrode puller) containing the test solution. Signals were acquired with a pre-amplifier (TasteProbe; Syntech, Germany), amplified (AC amplifier 1800, A-M Systems, USA), digitized at 30 kHz (DT9803 Data Translation) and stored using DataView (version 11.5). Pesticides (IMD, CLO, TMX, SFX) were tested in a background of 10% OSR. Pesticides were tested using a concentration gradient (1, 10, 100, and 1000 nM) and also at 0.1 mM. Additionally, QUI was tested in 10% OSR at concentrations of 0.1 and 1.0 mM. A minimum inter-stimulus interval of 3 min was used to prevent sensory

adaptation. We obtained recordings from n=12 bee per compound and tested 2-4 sensilla per mouthpart location (6-12 sensilla per bee). To ensure the pesticides or QUI were not imposing a toxic effect on the taste sensilla, we included recordings at the beginning and end of each stimulation series with 10% OSR (SI Figure 1).

Spike detection

Spikes from GRNs on the galea were extracted as described previously (Parkinson et al., 2022b). Briefly, after band-pass filtering (300-2500 Hz, second order butterworth filter) and normalization, spikes were detected using the peakfinder function with adequate thresholds manually set for each recording. Interspike intervals were used to detect the end of burst positions (EOB). Using this method, we detected three GRNs within the galeal electrophysiological recordings, as seen previously (Parkinson et al., 2022b). GRNs of the labial palps were non-bursting. A custom-written routine in Matlab (The MathWorks) was used to differentiate spiking units (i.e. GRNs) within these recordings. Spiking units were detected as described previously, and visual inspection of the data suggested that two GRNs were present in these recordings. The spike waveforms for each recording were compared to differentiate the spikes from the putative units. Waveforms were aligned from the peak +/- 2 ms, and the Matlab singular value decomposition (SVD) function was used to obtain the principal components of the spike waveforms. Waveforms were then projected onto the space spanned by the first two principal components, and K-means clustering was used to assign the waveforms to units for each recording. Using this method, two (or in some cases just one) GRNs were obtained from each recording, with the unit labelled GRN1 represented by larger waveform amplitudes and higher spike frequencies in response to sugars. GRN responses from individual animals were averaged across sensilla recorded in each location (Gal, LP_{III}, LP_{IV}).

Statistical analyses and data presentation

We performed all further analyses in R version 4.2.1 (Team, 2016). Average firing rates of the 7 GRN types (Gal GRNs 1-3, LP_{III} GRNs 1-2, and LP_{IV} GRNs 1-2) across mouthpart locations were compared. Firing rates of a given GRN type were averaged

across sensilla from a single animal, and log transformed ($\log_{10}$(average_rate + 1)) to fit a normal distribution. We compared electrophysiological responses across stimuli using linear mixed effects models (LME, lmerTest toolbox) (Kuznetsova et al., 2017) with Gaussian distributions and "bee ID" as the random effect (avg_rate~stimulus*GRN+(1|BeeID)). Models with non-significant interaction terms were re-run without the term (avg_rate~stimulus+GRN+(1|BeeID)). *Post hoc* analyses were performed using estimated marginal means (emmeans toolbox, (Lenth et al., 2018)) with Tukey's adjustment for family-wise error rates. Significant effects were denoted with asterisks (*, <0.05; ** <0.001; ***, <0.0001).

The temporal patterns of GRN activity over time was also assessed by extracting spike rates for each GRN within 0.1 s bins from 0.1 to 1.1 s after stimulation. Firing rates within each bin were averaged by animal for a given GRN type. As the labial palp GRNs did not display a bursting pattern, we averaged the firing rate within each bin across all four labial palp GRNs. The pattern of bursting of galeal GRNs (GRNs 1 and 2) was assessed using two measures: the burst length (number of GRN1 spikes per burst) and burst rate. Firing rate histograms were constructed using these measurements over 1 s of stimulation, and stimuli were compared with LME models (temporal_parameter~stimulus+bin+(1|BeeID)). Significant differences in the slopes between stimuli were denoted on plots with letters. To assess differences in the complete temporal code of all 7 GRNs across mouthparts, we aligned the binned spike times in series for each GRN. For each animal and stimulus, there was a vector of 70 bins (ten 0.1s bin per GRN type, aligned for 7 GRNs). To reduce the variability in responses between animals and balance the scale of responses across GRNs, we normalized the responses across GRN replicates within each animal by dividing by the average responses of each GRN to 10% OSR. The normalized responses of single GRNs were then averaged across replicates for each animal. We used t-distributed stochastic neighbour embedding (t-SNE) to reduce the dimensionality of the temporal data to two axes for each dataset (OSR vs sucrose, QUI, and pesticides). Results from t-SNE were then clustered to reveal grouping of responses by stimulus. Optimal cluster count was predicted using Monte Carlo reference-based consensus clustering (M3C,

(John et al., 2020)), an unsupervised learning technique that aggregates across k-means clustering runs. Optimal clustering (if k>1) was included on t-SNE plots.

Feeding behaviours were compared using t-tests, ANOVA with Tukey's *post hoc* multiple comparisons (HSD), or LME for concentration gradient comparisons of pesticide mixtures with "colony" as a random effect. Behavioural data that was not normally distributed was log transformed. For all boxplots in the paper, the median is indicated by a line, bounds of the box mark the 1st and 3rd quartile, and whiskers extend to 1.5 times the interquartile range. Individual data points are drawn.

Results

GRNs encode differences in sugar solution composition

Responses of bumblebee galeal GRNs to individual sugar compounds have previously been described (Miriyala et al., 2018; Parkinson et al., 2022b). Here, we tested whether a mixture of fructose, glucose, and negligible amounts of sucrose that mimics OSR nectar altered the GRN spiking responses compared to sucrose alone. We also expanded our investigation to include responses form GRNs in the labial palps (Figure 1 A). We found that GRNs in each location had specific patterns of activation that characterized their responses to sugar stimulation (Figure 1 B). Stimulation of galeal sensilla with sucrose or with OSR nectar produced bursts of spikes resulting from the co-activation of two GRNs (Gal1 and Gal2), as we found for individual sugars previously (Miriyala et al., 2018; Parkinson et al., 2022b, Figure 1 B). Each labial palp sensillum (LP_{III} and LP_{IV}) contained two sugar-sensitive GRNs (LP_{III} 1 and 2, LP_{IV} 1 and 2), but these GRNs exhibited tonic firing patterns in response to stimulation instead of bursts of spikes (Figure 1 B). The spiking rates averaged over 1 s stimulation of Gal1 and the labial palp GRNs were unchanged towards the two stimuli, but the average rate of Gal2 and Gal3 when stimulated with sucrose was lower than the rate for stimulation with 10% OSR (Figure 1 C, LME, stimulus*GRN $F_{6,1607} = 9.16$, $p < 0.0001$). (Note: GRN3 was active only when stimulated with 10% OSR, but not by an equimolar sucrose solution, Figure 1 C).

We compared the time-varying responses of GRNs using binned spikes (0.1 s bins over 1 s stimulation). We found that the rate of adaptation, measured by the change in the interspike interval of labial palp GRNs were not significantly different for 10% OSR or sucrose (Figure 1 D, stim: $F_{1,461}$ = 3.11, p > 0.05; time, $F_{1,450}$ = 586, p < 0.0001; SI Figure 1 B). However, galeal GRN burst structure (Gal1 and Gal2) differed between stimuli (Figure 1 E, stim*GRN: $F_{1,938}$ = 13.8, p = 0.0002, time: $F_{1,938}$ = 1.42, p > 0.05). OSR elicited a 20% higher burst rate (i.e., Gal2 rate, SI Figure 1 C) and shorter bursts (i.e., fewer Gal1 spikes per burst, SI Figure 1 D), although the rate of adaptation of Gal1 did not differ as a function of stimulus (Figure 1 E). To understand if the population of neurons we recorded from contained information about stimulus identity, we combined the temporal responses binned at 100 ms intervals over 1 s of recording of all 7 GRNs across mouthparts using a clustering algorithm (t-SNE and k-means clustering). The algorithm predicted two statistically separate stimulation groups, one for OSR and one for sucrose (Figure 1 F).

In spite of the differences observed in GRN responses, the total volume of the 10% OSR and equimolar sucrose solutions (1.79 M, Figure 1 G) consumed by bumblebees was not significantly different in the free-feeding assay (Figure 1 H, t-test, t = -1.44, df = 28, p = 0.49). We also did not observe a difference in the duration of the first feeding bout (Figure 1 I, t-test, t = -0.50, df = 27, p = 0.081), or the total time the bees spent in contact with the solutions over 2 min (Figure 1 J, t-test, t = -0.837, df = 27, p = 0.38). We also tested whether the concentration of these sugar solutions influenced behaviour using a concentration gradient of OSR and sucrose solutions at 2.0, 1.5, 1.0, 0.5 M and water. A greater volume of sucrose was consumed for the 1 M and 1.5 M concentrations than for the OSR solution, but there was no difference at any other concentration (SI Figure 2). First bout and total contact duration were not significantly different.

Labial palp GRNs may enable bitter detection

QUI is routinely used to test an animal's sensitivity to bitter substances. Here, we used a concentration series of QUI in 10% OSR solution to test how mouthparts GRNs

respond to QUI, so that we could use this as a positive control for our tests with pesticides. A 1 mM QUI concentration suppressed all galeal and labial palp GRNs, while 0.1 mM QUI suppressed the activity of $LP_{III}2$ and $LP_{IV}2$ alone (Figure 2 A, LME, stimulus*GRN $F_{12,1581}$ = 11.3, p < 0.0001, SI Figure 3 A-C). The rate of adaptation, however, of the labial palp GRNs was faster when they were stimulated with the 0.1 mM QUI solution (Figure 2 B, stim*time: $F_{1,450}$ = 13.8, p = 0.0002). Galeal GRN burst structure was affected by the addition of QUI (Figure 2 C, stim*GRN: $F_{2,1116}$ = 308, p < 0.0001, time: $F_{1,1116}$ = 0.062, p = 0.803; SI Figure 3 B-C). Gal1 adapted faster when stimulated with 0.1 mM QUI compared to QUI, although there was no effect on Gal2 (Figure 2 C). Clustering of all GRN responses predicted two groups, with the responses to 1 mM QUI separating from the responses to 10% OSR and 0.1 mM QUI (Figure 2 D). OSR and 0.1 mM QUI were not significantly different.

The detection threshold observed in the behaviour experiments was lower than predicted by the t-SNE clustering but consistent with our measurements of adaptation in labial palp neurons. Bumblebees consumed significantly less OSR solution when it contained 0.1 mM QUI, while 1 mM QUI was completely deterrent (Figure 2 E, LME, concentration: $F_{2,35}$ = 49.1, p < 0.0001). However, the structure of feeding towards 1 mM QUI was similar to the results found for the cluster analysis of the GRNs: bees tested with 1 mM QUI exhibited much shorter average first feeding bout duration (Figure 2 F, LME, concentration: $F_{2,40}$ = 18.2, p < 0.0001) and shorter average cumulative bout duration (Figure 2 G, LME, concentration: $F_{2,36}$ = 61.5, p < 0.0001) than those fed with OSR or 0.1 mM QUI solution.

Extremely high concentrations of pesticides in OSR nectar reduce the rate of spiking of GRNs

In our previous work (Kessler et al. (2015), field-relevent concentrations of neonicotinoid pesticides were not detected by galeal GRNs. Here, we used OSR instead of sucrose and included sulfoxaflor. We also extended this experiment to test the labial palps. As before, we found no significant difference in galeal GRN responses between the control (OSR) solution and all of the solutions containing pesticides at field-relevant

concentrations (SI Figure 4). No significant differences were detected in the responses of the labial palp neurons to the pesticide solutions (SI Figure 4).

To test whether all concentrations of pesticides go undetected by bees, we stimulated GRNs with 0.1 mM of each pesticide mixed with 10% OSR. Such concentrations are 10-100k fold greater than has been reported for neonicotinoids from the nectar and pollen of agricultural crops and are at least 1k fold greater than the LD_{50} values for bumblebees (Cresswell et al., 2014; Mundy-Heisz et al., 2022; Siviter et al., 2022). Sulfoxaflor, however, is present at much higher concentrations in the field (e.g., 71.4 µM, U.S. Environmental Protection Agency (EPA), 2014)). Stimulation with extremely high concentrations of TMX reduced the average firing rates of LP_{III} GRN2 and LP_{IV} GRN2; none of the other pesticides affected the average GRN firing rates (Figure 3 A, LME, stimulus*GRN: $F_{24,2139} = 1.65$, $p = 0.024$.)

We also examined how the temporal response of galeal and labial palp neurons was influenced by stimulation with extreme concentrations of the pesticides. Labial palp GRNs adapted faster when IMD or TMX were added to 10% OSR (Figure 3 B, stim: $F_{1,821} = 49.9$, $p < 0.0001$; time, $F_{1,808} = 571$, $p < 0.0001$), and firing rates of labial palp GRNs over 1 s were significantly reduced (SI Figure 5 A). Gal1 and Gal2 spiking and adaptation rates were affected by CLO and IMD (Figure 3 C, stim*GRN: $F_{4,1653} = 3.47$, $p = 0.0078$; time, $F_{1,1653} = 2.33$, $p = 0.127$). Galeal GRN bursting rate was slightly reduced when stimulated with OSR mixed with CLO or IMD (SI Figure 5 B), while the burst length was not affected by the addition of pesticides (SI Figure 5 C). We used the same clustering algorithm that was able to differentiate the responses to sucrose and OSR. Clustering using all of the data for each of the sensillum types failed to separate the pesticide responses from responses to the control (10% OSR, Figure 3 D).

Bumblebees readily consume pesticides in nectar

We assessed whether the pesticides were aversive in the range of values that included field-realistic concentrations (0 - 1000 nM) and one of the extreme values (0.1mM) added to a 10% OSR solution. Field-relevant concentrations of the pesticides in OSR

nectar did not deter the bees from feeding, as the presence of these compounds did not significantly alter the amount of food consumed (LME, concentration: $F_{4,297}$ = 0.209, p = 0.933), first bout duration (LME, concentration: $F_{4,290}$ = 0.648, p = 0.629) or cumulative bout duration (LME, concentration: $F_{4,288}$ = 0.310, p = 0.871) over the 2 min assay period (Figure 4 A-C). Importantly, we also tested feeding behaviour using an extreme concentration (0.1 mM) of the pesticides in OSR. Even at this very high concentration, we did not observe a significant difference in the amount of food consumed (AOV: $F_{4,78}$ = 0.975, p = 0.426), first bout duration (AOV, $F_{4,74}$ = 0.403, p = 0.806), or cumulative bout duration (AOV, $F_{4,74}$ = 1.22, p = 0.309) over 2 min (Figure 4 D-F).

Discussion and conclusions

Using an assay developed to study avoidance behaviour towards bitter compounds in bumblebees (Ma et al., 2016), we show that bumblebees do not avoid drinking OSR nectar solutions even when very high concentrations of common pesticides are present. Our electrophysiology assay also showed that the only concentrations that produced a measurable reduction in the spiking of sugar-sensing GRNs were extremely high concentrations of these pesticides. These small changes in the rate of spiking did not translate into features that the clustering algorithm could use to differentiate pesticide laced stimuli from the control OSR solution, however. Likewise, bumblebees were not deterred from drinking the OSR solutions with high pesticide concentrations. From these data, we conclude that the buff-tailed bumblebee's mouthparts do not have mechanisms for the detection and avoidance of common cholinergic pesticides in nectar, as previously reported by Kessler et al. (2015).

In most insects, bitter, non-nutrient compounds are detected by specialized GRNs which spike in response to stimulation (Weiss et al., 2011). Bitter compounds can also be detected through the suppression of the sugar-sensing GRNs (French et al., 2015). In the present experiments, we were mainly testing for the reduction of GRN spiking caused by the suppression of sugar-sensing GRNs, as all of the 'bitter' compounds we tested were presented to the sensilla in OSR nectar (a mixture of primarily fructose and

glucose). The known bitter compound, QUI, clearly suppressed the activity of sugar-sensing GRNs in both labial palps and the galea, but it didn't measurably alter the burst pattern of firing of the galeal GRNs. Importantly, our new data were able to confirm that field-relevant concentrations of pesticides did not significantly alter the pattern or rate of spiking of galeal or labial palp GRNs towards a nectar solution.

We used a clustering algorithm that integrated input from all the sensilla we recorded from over a 1 s time interval with every stimulus to identify whether population-level input made it possible to differentiate the stimuli. Although we were able to measure small but significant changes in the responses of both labial palp and galeal neurons caused by the high concentrations (100 µM) of IMD, SFX, and TMX, this effect was not sufficient for the clustering algorithm to form classes of distinct stimuli for the OSR-pesticide mixtures. This is similar to what we observed for 0.1 mM QUI; though a small change in firing was detected, the classification algorithm did not differentiate it from OSR. Our electrophysiological recordings are the first to report GRN responses from the bumblebee's labial palps. The labial palps in other insects such as locusts are used to detect both phagostimulants and deterrant compounds (Blaney and Chapman, 1970), so we might have rationally expected to observe labial palp GRNs that spike in response to QUI and cholinergic pesticides, but we did not.

It is interesting to note that in the case of all bitter compounds tested, the output of the clustering algorithm matched the behaviour of the bees, as the bees themselves did not reject any of the pesticide solutions or the 0.1 mM QUI solution. This could indicate that that small differences detected at the sensory periphery do not translate into a sufficient signal across the whole population of gustatory neurons to produce an aversion to foods containing potential toxins. However, it is worth noting that the OSR background solutions in both cases were different: in the behavioural experiments the concentration of OSR was an average value of that naturally found in nectar. Our physiology experiments were performed using a 10% dilution of this solution. Different solutions were used because it was not possible to record from neurons with such a concentrated

sugar solution, and in behavioural experiments, most bumblebees do not find 10% OSR sufficiently phagostimulatory to feed.

Our new data also indicate that gustatory coding is more than the presence or absence of spikes arising from GRNs tuned to detect particular tastants. In bumblebees, it is clear that the pattern of spiking itself conveys information which is a feature that enables the brain to distinguish gustatory stimuli (Parkinson et al., 2022b). This supports the idea that encoding of gustatory stimuli is accomplished by the whole population of GRNs on a given body part (e.g. the proboscis) as was observed in multichannel recordings from the adult hawkmoth maxillary nerve (Reiter et al. 2015). Thus, activity across the mouthparts GRN population that includes temporal input over time is likely to be used by the brain to differentiate taste stimuli and to facilitate the valuation of food quality. Our new data testing the difference between a nectar stimulus composed of a mixture of sugars (OSR) and sucrose clearly illustrates this. The changes in the rate of bursting and spiking in the galeal and labial palps were sufficient for the clustering algorithm to classify sucrose and OSR as separate stimuli. Although our behavioural assay did not show a difference, we would not expect it to, as it is an assay developed to study food rejection behaviour by bees, not differences in phagostimulation. We predict that these two solutions are completely distinguishable by bumblebees; this has exciting implications for the bee's ability to distinguish naturally occurring nectar of different flowering plant species. Future studies will be necessary to confirm this.

Previously, Arce et al. (2018) reported that *B. terrestris* were capable of selectively foraging on 30% w/v sucrose solutions containing thiamethoxam. They challenged our previous conclusion that honeybee and bumblebee preferences for solutions containing TMX were accomplished in the absence of taste cues in our choice assays (Kessler et al. 2015). There are important differences in the experiments of Arce et al. (2018) and those we present now. They used gravity feeders in an enclosed arena in which bees could consume solutions *ad libitum*, switching the feeders between training and testing phases to ensure bees could not predict where the TMX laced food was. The feeders did not have visual or olfactory cues, so they deduced that the bees were capable of

tasting the presence of TMX in the solution. However, gravity feeders do not simulate how bees feed on real flowers. Such feeders have large openings in which several bees can feed simultaneously; in this setting, bees can contact the solution with all body parts, including the tarsi and antennae. It is possible that the sensilla on the antennae or tarsi could detect TMX, but unlikely. In honeybees, bitter detection in these locations is limited and is only observed when the sensilla are contacted with concentrations of compounds like QUI that are >1 mM (de Brito Sanchez et al., 2005; de Brito Sanchez et al., 2014). Field-relevant concentrations of the pesticides we tested are between 3-6 orders of magnitude lower in concentration (see Kessler et al. 2015 for review); such dilute concentrations of a bitter compound present in a highly concentrated sugar solution would be difficult for most organisms to detect. The post-ingesitve mechanisms that produce bee preferences for foods containing neonicotinoids remain to be discovered.

Floral morphology such as corolla length has often co-evolved with particular groups of pollinators with longer mouthparts; a long corolla protects nectar when visitors are efficient and reliable pollinators. In many flowers, nectar is hidden deep within the corolla such that the only contact that bumblebees have with it is via the distal end of the proboscis (also the location where most of the sensilla are). For example, in OSR flowers, nectaries are located at a depth of 5-8 mm (Cresswell et al., 2001) and the nectar cannot be contacted otherwise unless the bee bites through the petals. In addition, bees learn to handle flowers quickly to improve their foraging efficiency (Heinrich, 1976) and even extend the proboscis in anticipation of entering the corolla prior to landing. Thus, they are unlikely to contact nectar using gustatory sensilla on their antennae or tarsi while foraging. For this reason, it is likely that nectar palatability is largely determined by the sensilla on the proboscis. Based on our current results and those of previous studies (Sculfort et al., 2021; Tiedeken et al., 2014), we predict that bumblebees have a limited ability to detect naturally-occurring concentrations of toxic or bitter compounds in nectar. Future studies that survey a greater variety of compounds will be necessary to confirm this.

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Figure legends

Figure 1: Electrophysiological and behavioural responses to sucrose and oilseed rape (OSR) nectar.

A: Diagram of the bumblebee's mouthparts from which tip-recordings were made, including the galea, and segments III and IV of the labial palps. Tip-recordings were made from the longer 'A-type' sensilla.

B: Filtered electrophysiological recordings from galeal (Gal), labial palp segment III (LP_{III}), and labial palp segment IV (LP_{IV}) sensilla. Spikes from GRN 1 at each location are labeled with blue circles, GRN 2 spikes in green, and GRN 3 spikes in magenta (only two GRNs present in labial palp recordings).

C: Average firing rates of GRNs from sensilla on the galea (Gal), segment III of the labial palps (LP_{III}), and segment IV (LP_{IV}) over 1 s of stimulation with 10% OSR or an equimolar (0.173 M) sucrose solution (SUC). Mean and standard deviation illustrated with black bars, data shown with coloured points. Asterisks represent significant differences between SUC and OSR.

D: Linear regression of inter-spike intervals per 0.1 s bin of labial palp GRNs versus time. Slope of regression is the adaptation rate. Shading is standard error. No significant difference between the adaptation rate when stimulated with OSR versus sucrose.

E: Firing rates of Gal1 versus Gal2 over 1 s stimulation with 10% OSR and SUC. Points represent mean rate in each 100 ms bin across all trials. A black marker highlights the

first bin (i.e., time = 100 ms). *Post hoc* comparisons showed that Gal2 firing rates were significantly different between stimuli.

F: t-SNE of all GRN responses for each animal following stimulation with OSR (gray) or SUC (orange) and k-means clusters (k=2, predicted by Monte Carlo reference-based consensus clustering) in gray shading.

G: Image of an untethered bumblebee in a holding tube feeding from a capillary in the 2-min feeding assay.

H: Total volume consumed of 1.79 M SUC or 100% OSR of freely moving bumblebees during 2 minutes.

I: The duration of the first feeding bout duration of bumblebees feeding on SUC or OSR.

J: The cumulative duration of feeding bouts within a 2 min period.

Figure 2: Quinine shuts down GRN and behavioural responses to sugars.

A: Average firing rates of 7 GRNs from the galea (Gal), and labial palps (LP_{III}, LP_{IV}) over a 1 s stimulations with 10% OSR (OSR), 10% OSR plus 0.1 mM quinine (QUI 0.1), and 10% OSR plus 1 mM quinine (QUI 1). Mean and standard deviation illustrated with black bars, data shown with coloured points (n = 12). Asterisks represent significant differences between stimulus and OSR.

B: Linear regressions of inter-spike intervals per 0.1s bin of labial palp GRNs versus time illustrating the adaptation rate, with SEM in grey shading. The addition of 0.1 mM QUI to OSR significantly affected labial palp adaptation. 1 mM QUI not shown as there was insufficient spiking to calculate adaptation.

C: Firing rates of Gal1 versus Gal2 over 1 s stimulation. Points represent mean rate in each 100 ms bin across all trials. A black marker highlights the first bin (i.e., time = 100 ms). *Post hoc* comparisons showed that only Gal1 (not Gal2) firing rates were significantly different at 0.1 mM QUI, while both were affected by 1.0 mM QUI.

D: t-SNE of all GRN responses for each animal following stimulation with 10% OSR, QUI 0.1 or QUI 1, and k-means clusters (k=2, predicted by Monte Carlo reference-based consensus clustering) in gray shading.

E: Volume consumed by freely-moving bumblebees of 100% OSR, OSR plus 0.1 mM QUI, or OSR plus 1mM QUI over a 2 min period (n = 15 bees/group). Asterisks denote results of Dunnett's test.

F: First bout duration when feeding on OSR, QUI 0.1 or QUI 1 (n = 15 bees/group). Asterisks denote results of Dunnett's test.

G: Cumulative bout duration over a 2 min period of bumblebees feeding on OSR, QUI 0.1 or QUI 1 (n = 15 bees/group). Asterisks denote results of Dunnett's test.

Figure 3: Pesticides affect the temporal code of bumblebee GRNs.

A: Average firing rates of 7 GRNs from the galea (Gal) and labial palps (LP_{III}, LP_{IV}) over a 1 s stimulation with 10% OSR (OSR), or OSR plus 0.1 mM clothianidin (CLO), imidacloprid (IMD), sulfoxaflor (SFX), or thiamethoxam (TMX). Mean and standard deviation illustrated with black bars, and data shown with coloured points. Asterisks represent significant differences between stimulus and OSR.

B: Linear regressions of inter-spike intervals per 0.1s bin of labial palp GRNs versus time illustrating the adaptation rate, with SEM in grey shading.

C: Firing rates of Gal1 versus Gal2 over 1 s stimulation. Points represent mean rate in each 100 ms bin across all trials. A black marker highlights the first bin (i.e., time = 100 ms). *Post hoc* comparisons showed that only Gal1 firing rates were significantly different for CLO and IMD versus OSR, and Gal2 firing rates were affected by IMD only.

D: t-SNE of all GRN responses for each animal following stimulation with OSR, CLO, IMD, SFX, or TMX. Monte Carlo reference-based consensus clustering predicted an optimal cluster count of k=1 on the t-SNE.

Figure 4: Bumblebees do not avoid consuming pesticides in nectar at field relevant concentrations

A: The total volume consumed by freely moving bumblebees during 2 min of 100% OSR solutions containing increasing concentrations (nM) of CLO, IMD, TMX and SFX (n = 15 bees per group).

B: First feeding bout duration of OSR mixtures with increasing concentrations (nM) of pesticides (CLO, IMD, SFX, TMX, n = 15 bees per group).

C: Cumulative feeding duration during 2 min of OSR mixtures with increasing concentrations (nM) of pesticides (n = 15 bees per group).

D: Total volume consumed of OSR or OSR plus 0.1 mM CLO, IMD, TMX or SFX over 2 min by freely moving bumblebees (n = 15 bees per group).

E: First bout duration of bumblebees feeding on OSR and OSR mixed with 0.1 mM pesticides (n = 15 bees per group).

F: Cumulative bout duration over 2 min by bees feeding on OSR and OSR mixed with 0.1 mM pesticides (n = 15 bees per group).

References

Arce, A. N., Ramos Rodrigues, A., Yu, J., Colgan, T. J., Wurm, Y. and Gill, R. J. (2018). Foraging bumblebees acquire a preference for neonicotinoid-treated food with prolonged exposure. *Proceedings of the Royal Society of London B: Biological Sciences* **285**, 8–11.

Blaney, W. M. and Chapman, R. F. (1970). The functions of the maxillary palps of acrididae (Orthoptera). *Entomol Exp Appl* **13**, 363–376.

Calderone, N. W. (2012). Insect Pollinated Crops , Insect Pollinators and US Agriculture : Trend Analysis of Aggregate Data for the Period 1992 – 2009. *PLoS One* **7**, 24–28.

Carruthers, J. M., Cook, S. M., Wright, G. A., Osborne, J. L., Clark, S. J., Swain, J. L. and Haughton, A. J. (2017). Oilseed rape (Brassica napus) as a resource for farmland insect pollinators: quantifying floral traits in conventional varieties and breeding systems. *GCB Bioenergy* **9**, 1370–1379.

Chapman, R. F. and Sword, G. (1993). The importance of palpation in food selection by a polyphagous grasshopper (Orthoptera: Acrididae). *J Insect Behav* **6**, 79–91.

Cresswell, J. E., Hagen, C. and Woolnough, J. M. (2001). Attributes of individual flowers of Brassica napus L. are affected by defoliation but not by intraspecific competition. *Ann Bot* **88**, 111–117.

Cresswell, J. E., Robert, F. X. L., Florance, H. and Smirnoff, N. (2014). Clearance of ingested neonicotinoid pesticide (imidacloprid) in honey bees (Apis mellifera) and bumblebees (Bombus terrestris). *Pest Manag Sci* **70**, 332–337.

de Brito Sanchez, M. G., Giurfa, M., de Paula Mota, T. R. and Gauthier, M. (2005). Electrophysiological and behavioural characterization of gustatory responses to antennal "bitter" taste in honeybees. *European Journal of Neuroscience* **22**, 3161–3170.

de Brito Sanchez, M. G., Lorenzo, E., Su, S., Liu, F., Zhan, Y. and Giurfa, M. (2014). The tarsal taste of honey bees: behavioral and electrophysiological analyses. *Front Behav Neurosci* **8**, 1–16.

French, A. S., Sellier, M.-J., Ali Agha, M., Guigue, A., Chabaud, M.-A., Reeb, P. D., Mitra, A., Grau, Y., Soustelle, L. and Marion-Poll, F. (2015). Dual Mechanism for Bitter Avoidance in Drosophila. *Journal of Neuroscience* **35**, 3990–4004.

Garibaldi, L. A., Steffan-Dewenter, I., Winfree, R., Aizen, M. A., Bommarco, R., Cunningham, S. A., Kremen, C. and Carvalheiro, L. G. (2014). Wild Pollinators Enhance Fruit Set of Crops Regardless of Honey Bee Abundance. *Science (1979)* **339**, 1608–1611.

Gill, R. J., Ramos-Rodriguez, O. and Raine, N. E. (2012). Combined pesticide exposure severely affects individual- and colony-level traits in bees. *Nature* **491**, 105–8.

Goulson, D., Peat, J., Stout, J. C., Tucker, J., Darvill, B., Derwent, L. C. and Hughes, W. O. H. (2002). Can alloethism in workers of the bumblebee, bombus terrestris, be explained in terms of foraging efficiency? *Anim Behav* **64**, 123–130.

Goulson, D., Nicholls, E., Botías, C. and Rotheray, E. L. (2015). Bee declines driven by combined Stress from parasites, pesticides, and lack of flowers. *Science (1979)* **347**,.

Heinrich, B. (1976). The Foraging Specializations of Individual Bumblebees. *Ecol Monogr* **46**, 105–128.

Henry, M., Béguin, M., Requier, F., Rollin, O., Odoux, J., Aupinel, P., Aptel, J., Tchamitchian, S. and Decourtye, A. (2012). A common pesticide decreases foraging success and survival in honey bees. *Science (1979)* **336**, 348–350.

Huang, J. X. and An, J. D. (2018). Species diversity, pollination application and strategy for conservation of the bumblebees of China. *Biodiversity Science* **26**, 486–497.

John, C. R., Watson, D., Russ, D., Goldmann, K., Ehrenstein, M., Pitzalis, C., Lewis, M. and Barnes, M. (2020). M3C: Monte Carlo reference-based consensus clustering. *Sci Rep* **10**, 1–14.

Kessler, S. C., Tiedeken, E. J., Simcock, K. L., Derveau, S., Mitchell, J., Softley, S., Stout, J. C. and Wright, G. a. (2015). Bees prefer foods containing neonicotinoid pesticides. *Nature* **521**, 74–76.

Klein, A. M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C. and Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* **274**, 303–313.

Kuznetsova, A., Brockhoff, P. B. and Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models . *J Stat Softw* **82**,.

Lenth, R., Singmann, H., Love, J., Buerkner, P. and Herve, M. (2018). emmeans: Estimated Marginal Means, aka Least-Squares Means. *R package version*.

Ma, C., Kessler, S., Simpson, A. and Wright, G. (2016). A Novel Behavioral Assay to Investigate Gustatory Responses of Individual, Freely-moving Bumble Bees. *Journal of Visualized Experiments* **113**, e54233.

Meehan, T. D., Werling, B. P., Landis, D. A. and Gratton, C. (2011). Agricultural landscape simplification and insecticide use in the Midwestern United States. *Proceedings of the National Academy of Sciences* **108**, 11500–11505.

Miriyala, A., Kessler, S., Rind, F. C. and Wright, G. A. (2018). Burst Firing in Bee Gustatory Neurons Prevents Adaptation. *Current Biology* **28**, 1585-1594.e3.

Mundy-Heisz, K. A., Prosser, R. S. and Raine, N. E. (2022). Acute oral toxicity and risks of four classes of systemic insecticide to the Common Eastern Bumblebee (Bombus impatiens). *Chemosphere* **295**, 133771.

Muth, F., Gaxiola, R. and Leonard, A. S. (2020). No evidence for neonicotinoid preferences in the bumblebee Bombus impatiens. *R Soc Open Sci* **7**,.

Parkinson, R. H., Fecher, C. and Gray, J. R. (2022a). Chronic exposure to insecticides impairs honeybee optomotor behaviour. *Frontiers in Insect Science* **2**, 1–14.

Parkinson, R. H., Kessler, S. C., Scott, J., Simpson, A., Bu, J., Al-Esawy, M., Mahdi, A., Miriyala, A. and Wright, G. A. (2022b). Temporal responses of bumblebee gustatory neurons to sugars. *iScience* **25**,.

Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., Dicks, L. v., Garibaldi, L. A., Hill, R., Settele, J., et al. (2016). Safeguarding pollinators and their values to human well-being. *Nature* **540**, 220–229.

Schneider, C. W., Tautz, J., Grünewald, B. and Fuchs, S. (2012a). RFID tracking of sublethal effects of two neonicotinoid insecticides on the foraging behavior of Apis mellifera. *PLoS One* **7**, 1–9.

Schneider, C. A., Rasband, W. S. and Eliceiri, Kevin, W. (2012b). NIH Image to ImageJ: 25 years of Image Analysis. *Nat Methods* **9**, 671–675.

Sculfort, O., Gérard, M., Gekière, A., Nonclercq, D., Gerbaux, P., Duez, P. and Vanderplanck, M. (2021). Specialized Metabolites in Floral Resources: Effects and Detection in Buff-Tailed Bumblebees. *Front Ecol Evol* **9**,.

Siviter, H., Matthews, A. J. and Brown, M. J. F. (2022). A Combined LD50 for Agrochemicals and Pathogens in Bumblebees (Bombus terrestris [Hymenoptera: Apidae]). *Environ Entomol* **51**, 378–384.

Team, R. C. (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Tiedeken, E. J., Stout, J. C., Stevenson, P. C. and Wright, G. A. (2014). Bumblebees are not deterred by ecologically relevant concentrations of nectar toxins. *Journal of Experimental Biology* **217**, 1620–1625.

U.S. Environmental Protection Agency (EPA) (2014). Ecological Risk Assessment for the Registration Review of Sulfoxaflor. 79.

van der Sluijs, J. P., Simon-Delso, N., Goulson, D., Maxim, L., Bonmatin, J. M. and Belzunces, L. P. (2013). Neonicotinoids, bee disorders and the sustainability of pollinator services. *Curr Opin Environ Sustain* **5**, 293–305.

Vanbergen, A. J., Garratt, M. P., Vanbergen, A. J., Baude, M., Biesmeijer, J. C., Britton, N. F., Brown, M. J. F., Brown, M., Bryden, J., Budge, G. E., et al. (2013). Threats to an ecosystem service: Pressures on pollinators. *Front Ecol Environ* **11**, 251–259.

Wäckers, F. L., Alberola, J. S., Garcia-Marí, F. and Pekas, A. (2017). Attract and distract: Manipulation of a food-mediated protective mutualism enhances natural pest control. *Agric Ecosyst Environ* **246**, 168–174.

Weiss, L. A., Dahanukar, A., Kwon, J. Y., Banerjee, D. and Carlson, J. R. (2011). The molecular and cellular basis of bitter taste in Drosophila. *Neuron* **69**, 258–272.

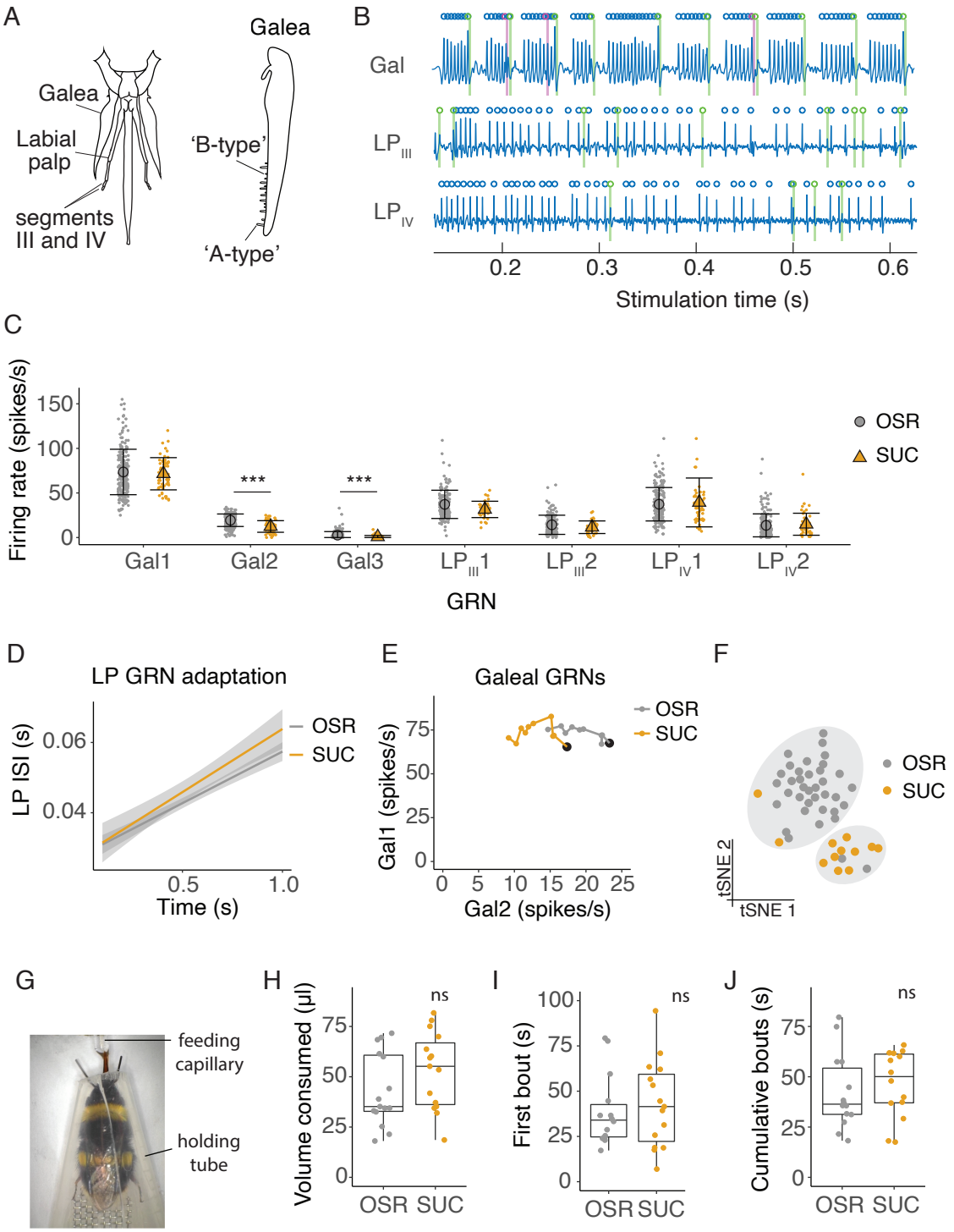
Williamson, S. M., Willis, S. J. and Wright, G. A. (2014). Exposure to neonicotinoids influences the motor function of adult worker honeybees. *Ecotoxicology* **23**, 1409–1418.

Wood, T. J. and Goulson, D. (2017). The environmental risks of neonicotinoid pesticides: a review of the evidence post 2013. *Environmental Science and Pollution Research* **24**, 17285–17325.

Wright, G. A., Mustard, J. A., Simcock, N. K., Ross-Taylor, A. A. R., McNicholas, L. D., Popescu, A. and Marion-Poll, F. (2010). Parallel reinforcement pathways for conditioned food aversions in the honeybee. *Current Biology* **20**, 2234–2240.

Wright, G. A., Softley, S. and Earnshaw, H. (2015). Low doses of neonicotinoid pesticides in food rewards impair short-term olfactory memory in foraging-age honeybees. *Sci Rep* **5**, 1–7.

Figure 1


A
Galea
Galea
Labial palp
segments III and IV
'B-type'
'A-type'
B
Gal
LP III
LP IV
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0.3
0.4
0.5
0.6
Stimulation time (s)
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Firing rate (spikes/s)
150
100
50
0
***
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OSR
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Gal1
Gal2
Gal3
LP III 1
LP III 2
LP IV 1
LP IV 2
GRN
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0.06
0.04
OSR
SUC
0.5
1.0
Time (s)
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Galeal GRNs
Gal1 (spikes/s)
75
50
25
0
OSR
SUC
0
5
10
15
20
25
Gal2 (spikes/s)
F
OSR
SUC
tSNE 2
tSNE 1
G
feeding capillary
holding tube
H
Volume consumed (µl)
75
50
25
0
ns
OSR
SUC
I
First bout (s)
100
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50
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Cumulative bouts (s)
75
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25
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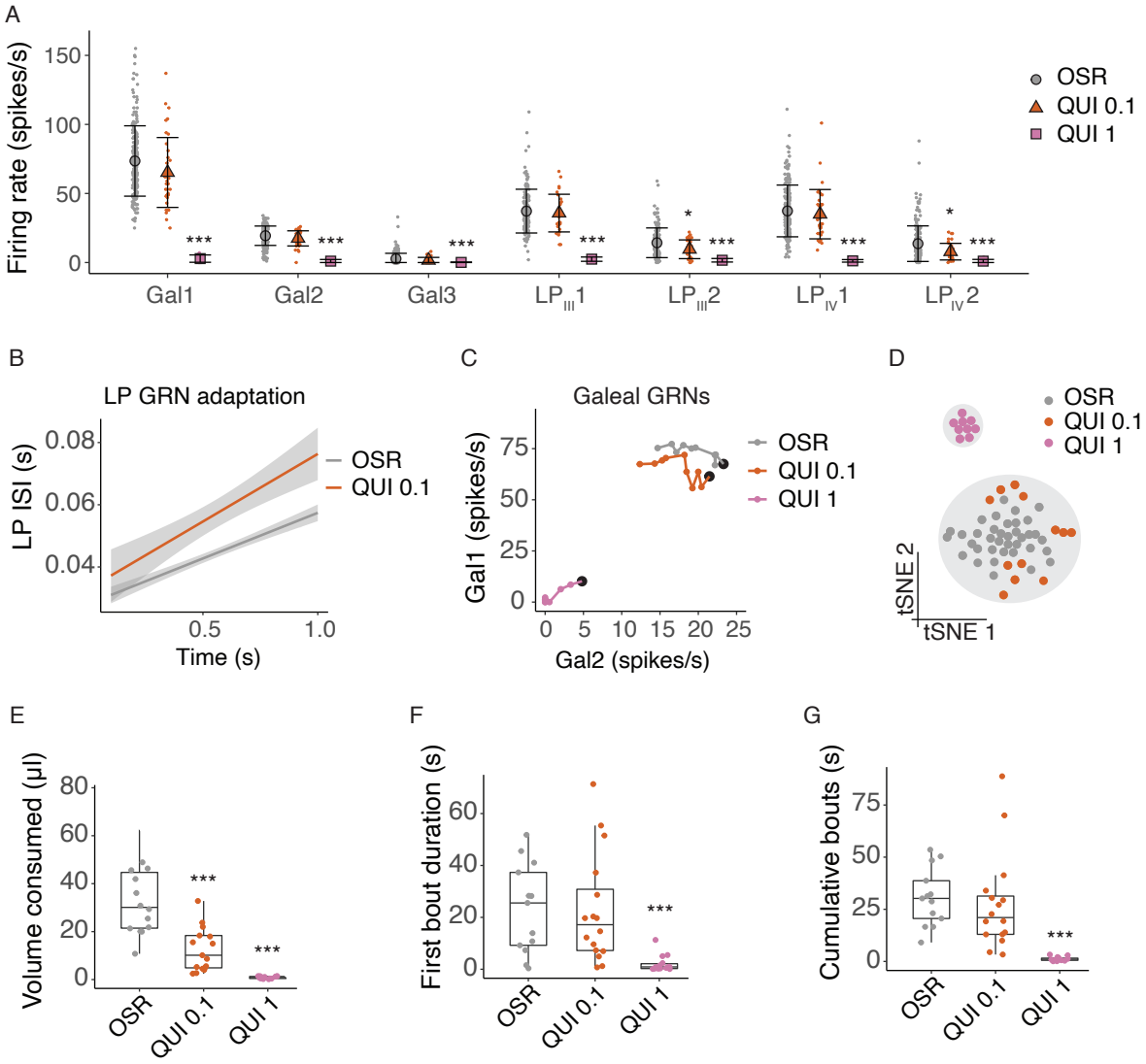
ns
OSR
SUC

Figure 2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*
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Gal3
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LP$_{III}$2
LP$_{IV}$1
LP$_{IV}$2
B
LP GRN adaptation
LP ISI (s)
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0.5
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Time (s)
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Galeal GRNs
Gal1 (spikes/s)
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Gal2 (spikes/s)
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tSNE 2
tSNE 1
E
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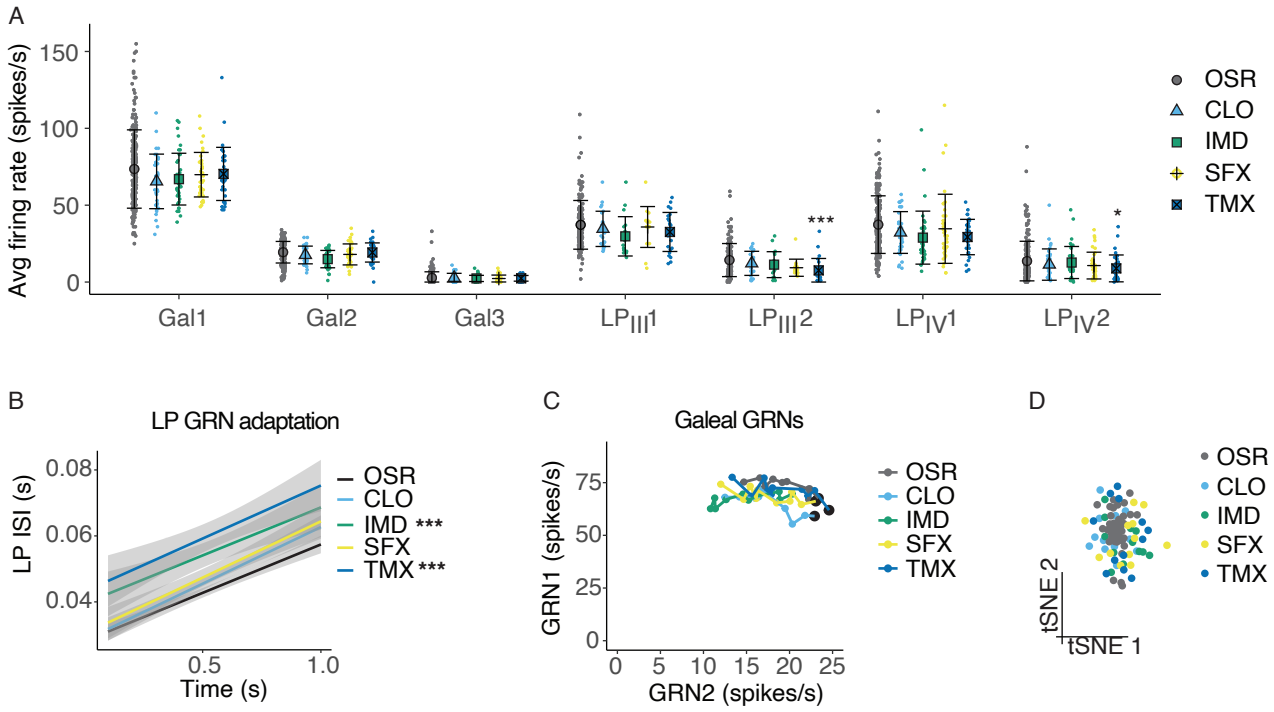
F
First bout duration (s)
G
Cumulative bouts (s)

Figure 3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Avg firing rate (spikes/s)
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LPIII1
LPIII2
LPIV1
LPIV2
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CLO
IMD
SFX
TMX
B
LP GRN adaptation
LP ISI (s)
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Galeal GRNs
GRN1 (spikes/s)
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GRN2 (spikes/s)
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CLO
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SFX
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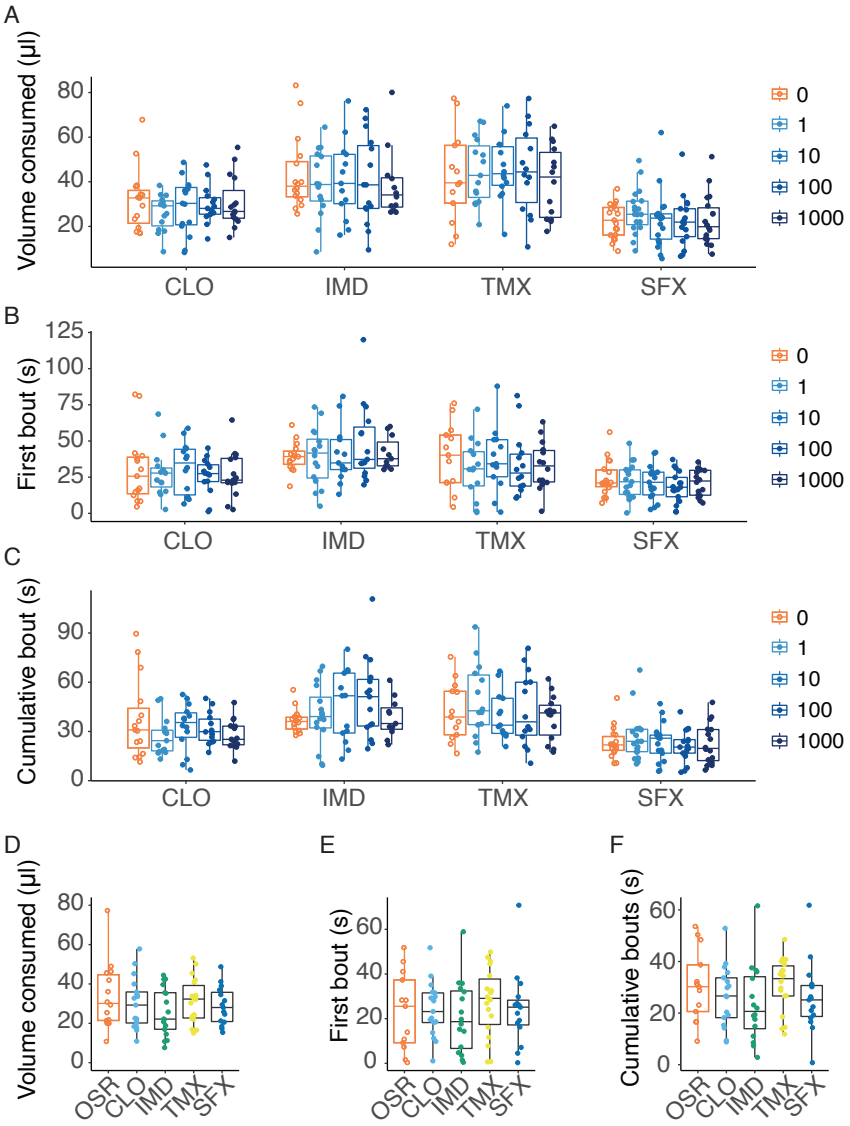
Figure 4


A
Volume consumed (µl)
80
60
40
20
CLO
IMD
TMX
SFX
0
1
10
100
1000
B
First bout (s)
125
100
75
50
25
0
CLO
IMD
TMX
SFX
0
1
10
100
1000
C
Cumulative bout (s)
90
60
30
0
CLO
IMD
TMX
SFX
0
1
10
100
1000
D
Volume consumed (µl)
80
60
40
20
0
OSR
CLO
IMD
TMX
SFX
E
First bout (s)
60
40
20
0
OSR
CLO
IMD
TMX
SFX
F
Cumulative bouts (s)
60
40
20
0
OSR
CLO
IMD
TMX
SFX