PROCEEDINGS OF THE ROYAL SOCIETY B | BIOLOGICAL SCIENCES

Neural coding merges sex and habitat chemosensory signals in an insect herbivore

Journal:	*Proceedings B*
Manuscript ID:	RSPB-2013-0267.R1
Article Type:	Research
Date Submitted by the Author:	n/a
Complete List of Authors:	Trona, Federica; Swedish University of Agricultural Sciences (SLU), Plant Protection Biology - Chemical Ecology Division Anfora, Gianfranco; Fondazione Edmund Mach, IASMA Research and Innovation Centre Balkenius, Anna; SLU, Plant Protection Biology Bengtsson, Marie; SLU, Plant Protection Biology Tasin, Marco; SLU, Plant Protection Biology Knight, Alan; USDA, Yakima Agricultural Research Laboratory Janz, N; Stockholm University, Department of Zoology Witzgall, Peter; SLU, Dept Plant Protection Ignell, Rickard; SLU, Plant Protection Biology
Subject:	Neuroscience < BIOLOGY, Behaviour < BIOLOGY, Ecology < BIOLOGY
Keywords:	chemical communication, premating isolation, odour blends, intracellular recordings, functional imaging, Cydia pomonella
Proceedings B category:	Neuroscience

Neural coding merges sex and habitat chemosensory signals in an insect herbivore

Federica Trona 1,2,* Gianfranco Anfora 2, Anna Balkenius 1, Marie Bengtsson 1, Marco Tasin 1, Alan Knight 3, Niklas Janz 4, Peter Witzgall 1 and Rickard Ignell 1

1 Unit of Chemical Ecology, Department of Plant Protection Biology, SLU, Box 102, 23053 Alnarp, Sweden

2 IASMA Research and Innovation Centre, Fondazione Edmund Mach, 38010 S. Michele a/A (TN), Italy

3 Yakima Agricultural Research Laboratory, USDA, WA 98951, USA

4 Department of Zoology, Stockholm University, 10691 Stockholm, Sweden

* current address: Max Planck Institute for Chemical Ecology, Dept. Evolutionary Neuroethology, 07745 Jena, Germany

Running title: Pheromone and plant odour coding

Corresponding author: Federica Trona, Division of Chemical Ecology, Department of Plant Protection Biology, SLU, Box 102, 23053 Alnarp, Sweden. E-mail: federica.trona@slu.se

Keywords: chemical communication; reproductive isolation; magic trait; intracellular recordings; functional imaging; *Cydia pomonella*

Abstract

Understanding the processing of odour mixtures is a focus in olfaction research. Through a neuroethological approach, we demonstrate that different odour types, sex and habitat cues, are coded together in an insect herbivore. Stronger flight attraction of codling moth males, *Cydia pomonella*, to blends of female sex pheromone and plant odour, compared with single compounds, was corroborated by functional imaging of the olfactory centres in the insect brain, the antennal lobes (AL). The macroglomerular complex (MGC) in the AL, which is dedicated to pheromone perception, showed an enhanced response to blends of pheromone and plant signals, while the response in glomeruli surrounding the MGC was suppressed. Intracellular recordings from AL projection neurons that transmit odour information to higher brain centres, confirmed this synergistic interaction in the MGC. These findings underscore that, in nature, sex pheromone and plant odours are perceived

as an ensemble. That mating and habitat cues are coded as blends in the MGC of the AL highlights the dual role of plant signals in habitat selection and in premating sexual communication. It suggests that the MGC is a common target for sexual and natural selection in moths, facilitating ecological speciation.

1. Introduction

Odours typically are blends of several chemicals, in specific proportions, and the olfactory system decodes and discriminates these multidimensional signals rapidly and precisely. A current question is how odour blends are represented in olfactory circuits and to what extent the neural odour space reflects their ecological and evolutionary significance [1-4].

For reproduction, animals largely rely on two types of olfactory signals: sex pheromones distinguish conspecific mates, and habitat odours signal food sources for adults and offspring. Both sex and habitat odours are important mediators of premating reproductive isolation and speciation [5-7] and the neural circuitry underlying the integration of these two types of chemosensory cues is therefore an important target for sexual and natural selection. The interaction of sexual and natural selection is thought to be a powerful driver of speciation [8-10].

Insect herbivores are particularly suitable for studying the interaction between mating and habitat cues, especially host plant odours, due to the importance of these signals for their ecology and evolution. Host plant shifts have likely contributed to the remarkable diversification of plant feeding insects [11,12] and most of these rely on sex pheromones for mate finding [13,14].

Plant volatiles are recognized as sex pheromone modulators in many insect species [15,16]. Although the behavioural interaction between pheromones and host plant volatiles is well established, little is known about the neurophysiological correlates. Research on the processing of odour blends in the primary olfactory centre in the brain, the antennal lobe (AL), has focused mainly on sex pheromones or on plant volatiles, while the combination of these two classes of compounds is being investigated only since recently [17-19].

Separate investigation of pheromones and plant volatile stimuli has led to the idea of a functional specialization of sensory processing in the AL and that these two odour classes are represented in morphologically different regions of the AL of male moths. The macroglomerular complex (MGC) is considered to be dedicated to pheromone coding and the sexually isomorphic, ordinary glomeruli (OGs) to the coding of plant volatile information [20]. Recent studies in the silk moth *Bombyx mori* and the noctuid moth *Agrotis segetum*, however, do not corroborate a strict segregation of the two subsystems and indicate that the MGC receives lateral input from the AL [17-19].

In the codling moth *Cydia pomonella* (Lepidoptera, Tortricidae), a reconstruction of the glomerular structure of the AL, combined with electrophysiological recordings, suggested significant cross-talk between the pheromone and general odour subsystems [21]. Codling moth is a key pest of apple and its sex pheromone and the behavioural role of host plant volatiles have been carefully studied [22].

We investigated the neurophysiological mechanisms regulating the interaction between female sex pheromone and behaviourally active host plant odorants, using functional imaging of the AL and intracellular recordings (IR) of projection neurons (PNs) that transmit olfactory signals to higher brain centres. The finding that the MGC is dedicated to blends of social and environmental odours adds to our understanding of the role of chemosensory cues in premating reproductive isolation and plant-insect ecology. It also provides a new incentive for the refinement of sustainable insect control methods based on behaviour-modifying chemicals.

2. Materials and Methods

(a) Insects

Experiments were done with 2- to 3-day-old unmated codling moth *Cydia pomonella* (Lepidoptera, Tortricidae) males, which were reared for several generations on an artificial diet (Andermatt Biocontrol, Grossdietwil, Switzerland). The males were kept at 70±5% RH, 23°C, under a 16L:8D photoperiod and they were fed with sugar water.

(b) Odor stimuli

Test odours included the main component of codling moth female sex pheromone, codlemone, (*E*,*E*)-8,10-dodecadienol (>99.6% chemical and isomeric purity, Shin-Etsu Chemical Co., Tokyo) and three plant volatiles, (*E*)-ß-farnesene (93.4% pure), butyl hexanoate (97.8%, both from Bedoukian Research Inc., Danbury, USA) and pear ester, (*E*,*Z*)-2,4-decadienoate (87.4%, Sigma Aldrich).

For functional imaging and intracellular recordings, solutions of test compounds in 10 µl re-distilled hexane were applied on filter paper (0.5 x 1 cm), ca. 1 h before tests. After the solvent evaporated during 1 min, one or two filter papers (compound blends) were inserted into a Pasteur pipette. Codlemone was tested at amounts of 1 ng to 1 µg, plant compounds from 10 ng to 10 µg, in decadic steps. A continuous charcoal-filtered and moistened airstream (500 ml/min) passed through a glass tube (10 mm ID) over the antenna. A stimulus controller (SFC-2/b, Syntech, Kirchzarten, Germany) injected a 0.5-s puff (500 ml/min) through the pipettes into this glass tube. Odours were presented in randomized order. Pipettes with filter paper loaded with 10 µl of solvent were used as control.

For behavioural tests, synthetic compounds were released from a piezo sprayer [23]. Compound dilutions were delivered at 10 µl/min to a 20-µl glass capillary tube with a drawn-out tip. A piezo-ceramic disc vibrated the capillary at ca. 100 kHz, producing an aerosol, which evaporated a few cm downwind from the capillary tip at a constant rate and known chemical purity. Codlemone was tested at 0.1 pg/min and plant compounds at 1 and 100 pg/min.

(c) Behavioural assay

Wind tunnel experiments were conducted according to Knight *et al.* [24]. A fan pulled air through a charcoal filter, through a series of screens, at 0.25 m/s into the tunnel (1.6 x 0.6 x 0.6 m). Exhaust was expelled outside of the building. Room lighting was computer-controlled to gradually decrease during a 60 min dusk period, between full light level (1330 lux) and the dark period (25 lux). Ten batches of five moths were flown consecutively to each lure, during the first 3 h of the scotophase. Male moth behaviour was recorded for up to 6 min. The following types of behaviour were recorded: wing fanning, take-off, upwind flight and contact with the screen. Proportional data were adjusted with Bartlett's correction for small sample size. An angular transformation was used to normalize proportional data prior to analysis of variance (ANOVA) (Statistix 9, Analytical Software, Tallahassee, USA). An α-level of 0.05 was used to establish significance, Tukey's method was used to compare means.

(d) Functional imaging

Individual moths were secured in a 1 ml plastic pipette, with the head protruding from the narrow end, and fixed by dental wax (Surgident, Heraeus Kulzer Inc). The head capsule was opened between the antenna and the eyes; muscle, glands, trachea, neural sheath and the oesophagus were removed to expose the antennal lobes [25]. A calcium sensitive dye (Calcium green-2-AM dye) was dissolved in 20% Pluronic F-127 in dimethyl sulfoxide (Molecular Probes, Eugene, USA) and diluted in moth Ringer solution to 30 µM and then applied to the brain, leaving the preparation in a dark and cold (5°C) environment for 3 h.

Recordings were made in vivo after incubation and washing, using an Olympus microscope (20x air objective NA 0.50; filter settings: dichroic 500 nm, emission LP 515 nm). The preparation was illuminated at 475 nm. Stimulation started at frame 12 and lasted 1 s. Images were binned twice (320 x 240 pixel) to increase signal-to noise ratio. TILL Photonics imaging software (Gräfelfing, Germany) was used to record sequences of 40 frames (4 Hz, 200 ms exposure time) and noise was removed by a Gaussian filter. The response magnitude was calculated as the average $\Delta F/F$ for each frame, where F was estimated using a linear function fitted to the parts of the calcium fluorescence decay curve outside the potential response. The onset of the signal was set to the time of the first frame with a positive average $\Delta F/F$. For statistical analysis, a Kruskal-Wallis test was

followed by a Mann-Whitney U test with Holm-Bonferroni correction. A 3-D map of the codling moth AL [21] was used to link the active area to AL glomeruli.

(e) Intracellular recordings

Insect preparation and recordings were done as described by Trona et al. [21]. During recordings, the brain was super-fused with a pH 6.9 ringer solution delivered from a flow system. A silver ground electrode was in contact with the ringer solution. Using a micromanipulator, the AL was randomly penetrated with an electrode which was drawn from a heated glass capillary (0.5 mm i.d., Sutter Instrument Co., Novato, USA) with the tip filled with 1% neurobiotin (Vector Labs, Burlingame, USA) dissolved in 0.25 mM KCL and the remaining part was filled with 1 mM KCl.

After recordings, the AL interneuron was stained with a depolarizing current (0.5-0.7 nA, 15 min). The brain was dissected from the head capsule and stained following the protocol of Trona et al. [21]. Stained neurons were viewed in a laser scanning confocal microscope (Zeiss LSM 510, Carl Zeiss, Jena, Germany) with a 40x1.4 oil-immersion DIC objective. Alexa Fluor 488, fluorescein Avidin and Alexa Fluor 546 labelled structures were excited with an argon laser 488 nm (with a 505 nm long-pass filter) and a HeNe laser (with a 560 nm long-pass filter). Stacks of X-Y confocal images (1024 x 1024 pixel) were scanned at 0.7 µm step size.

Only complete recording sessions of the entire set of test stimuli were evaluated. Responses were calculated from the number of net-spikes during 500 ms (number of spikes 500 ms before stimulus onset subtracted from the number of spikes 500 ms after stimulus onset). Net-spikes in response to control were subtracted from the net-spikes in response to odour stimuli; blend responses were considered to be synergistic/suppressive when the number of net-spikes in response to blends was significantly higher/lower than the sum of net-spikes in response to the single compounds (G-test).

Results

(a) Behavioural assay

Blends of the main sex pheromone component, codlemone, and host plant volatiles attracted significantly more codling moth males than single compounds (figure 1). All three plant volatiles tested, (*E*)-ß-farnesene, butyl hexanoate and pear ester, elicited upwind orientation flights. Blending codlemone at 0.1 pg/min and plant volatiles at 100 pg/min significantly increased landings at the source, compared to codlemone alone (figure 1).

(b) Functional imaging

Calcium signals revealed distinct glomerular activity patterns for each odorant tested (figure 2). A threshold dose of codlemone (10 ng) elicited a significant response in the MGC, including the cumulus (Cu) and nearby satellite glomeruli (20 and 37; figure 2*b*). Plant volatiles alone did not elicit any response in the Cu, they instead activated satellite glomeruli and glomeruli outside the MGC (figure 2*c-e*). A threshold dose of pear ester (100 ng) was active in the satellite glomeruli 20 and 37, which also responded to codlemone (figure 2*c*) plus glomerulus 11 outside the MGC.

Blends of 10 ng codlemone plus 100 ng of each plant volatile compound produced a strong synergistic interaction in the Cu (figure 3*a,e*). This synergistic effect was not seen at a 10-fold higher dose (figure 3*a*). Although several of the glomeruli surrounding the Cu responded to plant volatiles and codlemone (figure 2*b-e, 3e*), there was no synergistic interaction in these glomeruli: outside the Cu, the activity elicited by blends was significantly lower than the sum of the activity elicited by the single compounds (figure 3*b-d*).

(c) Intracellular recordings

Figures 4 and 5 show the blend response of AL output neurons. Based on a dose-response test with single compounds (figure 4*a*), codlemone and individual plant volatiles were combined in a 1:10 ratio and 1:1000 ratio. The number of synergistic, suppressive and additive responses of AL neurons to blends of codlemone and plant volatiles, in the Cu and surrounding glomeruli is shown in figure 4*b,c*.

Analysis of 69 successful recordings demonstrates that odour blend interaction was not merely additive ($p<0.05$, G-test). Of the neurons showing a synergistic blend response, 52% responded to blends only, and not to single compounds. Suppressive responses comprised both a decreased excitatory phase (53%) and complete response suppression (47%) (figure 4*b*).

Twenty-nine neurons were successfully stained: 11 PNs arborizing in the Cu, 5 PNs in satellite glomeruli surrounding the Cu, 10 PNs in glomeruli outside the MGC and, in addition, 3 local interneurons (LNs). The Cu was innervated by uniglomerular PNs (figure 5*a*), and by one multiglomerular PN that also arborized in the satellite glomerulus 20 (figure 4*d*). Spike frequency histograms for selected PNs in response to compound blends are shown in figure 5. A statistical comparison of the blend effects in stained PNs revealed a significant difference: synergism occurred almost exclusively in the Cu, while blend stimulation of glomeruli outside the MGC mostly had a additive or suppressive effect (figures 4*c*, 5*c*).

Discussion

(a) Neural ensemble coding of sex pheromone and host plant odour in the MGC of the male moth AL

Understanding how stimulation with a blend of odorants generates a unique perception in the brain is a current research question. What adds to the complexity of olfactory coding is the integration of separate, independent signals - sex and habitat odours - which are together required to generate appropriate behavioural responses during mate-finding.

We combined functional imaging and intracellular recordings to study odour blend processing in the codling moth *C. pomonella*, and show that the behavioural synergism between sex pheromone and host plant odourants is mirrored neurophysiologically. The MGC in the AL integrates signals from conspecific insects with habitat odours and synergistic interactions between these two classes of odours occur both at the input and output level. This demonstrates that processing of sex pheromone and plant volatiles, which insects encounter as an ensemble in nature, does not employ functionally separate pathways [17,18].

Blend enhancement and suppression in the AL may stem from odour interference in antennal sensory neurons [19,26] and ultimately at the olfactory receptor level [27]. However, in codling moth, pheromone-plant volatile blends enhance the Cu response while they simultaneously suppress surrounding glomeruli in a "center-surround" fashion. Such complex coding may instead rely on lateral excitatory or inhibitory interconnections between glomeruli through local interneurons (LNs) [2,28]. Functional studies of LNs will be essential to understand olfactory processing in the AL.

Intracellular recordings of PNs, which connect the AL to higher brain centres, further corroborate that the MGC processes blends of plant volatiles and sex pheromone. Synergistic, blend-specific responses have been shown in the silk moth *B. mori* [17] and in codling moth, where PNs innervate the Cu and satellite glomeruli of the MGC [21].

An antagonistic interaction modality was shown in the black cutworm *A. ipsilon*. A floral volatile, which inhibits male attraction to pheromone, suppresses the pheromone response in the AL [18] and in PNs innervating the MGC [19]. This suggests that odours with different ecological roles may differently affect pheromone coding. A wiring diagram of input and output signals in the codling moth AL, based on a more complete panel of ecologically relevant odorants, from host and non-host plants or associated mutualistic microorganisms [29,30], will reveal whether glomerulus morphology and position in the AL correlates with the behavioural role of the respective key stimuli [31].

(b) Behavioural and ecological physiology of pheromone-plant odour blend perception

Mate recognition in insects, and especially in habitat-specific plant-feeding species, involves two main elements: sexual communication and recognition of larval and adult food plants, which frequently serve as rendezvous sites. Both mate and host finding largely rely on olfactory signals [14,32] which play a fundamental role in speciation [6,33].

In the codling moth, host plant odour is part of the mate finding signal. The plant volatiles chosen for this study are distinctive for the main hosts pear and apple, respectively. They mediate female attraction for oviposition [29,34-37] and they synergize male attraction to female sex pheromone. The MGC, in the olfactory centre of the moth brain, is the focal point for processing blends of pheromone and these plant signals.

Speciation is thought be facilitated by multiple-effect or "magic" traits, which are subject to divergent selection and which contribute to nonrandom mating [9,10]. The MGC interconnects mate and host choice and would accordingly be considered as a multiple-effect trait. Host choice seemingly is under divergent selection in codling moth, which forms distinct host races on apple, pear, walnut, plum and apricot. These differ in spring emergence and diapause initiation, in close association with host flowering and fruit maturation [38,39], and the genetically distinct walnut strain is adapted to toxic walnut metabolites [40-42]. Females of several strains preferentially oviposit on their respective host fruit [29,38].

A comparison of the female sex pheromones of closely related *Cydia* species further corroborates the role of plant volatiles in reproductive isolation. Only few species share the same pheromone, but these all feed on host plants belonging to different families. For example, pea moth *C. nigricana* (Leguminosae) and pear moth *C. pyrivora* (*Pyrus*), the sibling species of codling moth, use codlemone acetate (*E*,*E*)-8,10-dodecadienyl acetate, which is a strong pheromone antagonist in codling moth males [43].

Pheromone and host odour communication is highly integrated also in other insects, for example in *Drosophila* [44] and in bark beetles, where non-host volatiles, as opposed to host volatiles, have an antagonistic effect on host and mate finding [45]. In the two pheromone races of the European corn borer *Ostrinia nubilalis*, male preference for females of the same race leads to premating isolation [46,47], which is reinforced by preferential attraction to volatiles of their respective host plants, mugwort and maize [48,49].

Ecological speciation, following host plant shifts, has likely contributed to the remarkable diversity of phytophagous insects [11,33]. Our study provides physiological data that suggest that mate recognition systems evolve in concert with chemosensory adaptation to

new hosts and ecological niches, and that sexual selection cannot be separated from natural selection in male insect herbivores.

(c) Practical implication

Our knowledge of codling moth chemical ecology has led to the successful development of species-specific and safe population control by pheromone-mediated mating disruption. In spite of orchard applications on 200.000 ha [50], the behavioural mechanisms underlying the disruption of mating are still under debate [51,52] and a better understanding of them will give leads for improvement. Our study demonstrates that it will be useful to consider the physiological and behavioural effect of plant volatiles on mating disruption, since, in nature, pheromone and plant volatiles are perceived together.

Acknowledgments

We thank Valerio Mazzoni for advice on statistical analysis, and Duane Larson, USDA, ARS, Wapato, WA for assistance with the flight tunnel bioassays. This research is part of the Linnaeus programme Insect Chemical Ecology, Ethology and Evolution (IC-E3) funded by Formas and SLU.

References

1 Chittka, L. & Brockmann, A. 2005 Perception space – the final frontier. *Plos Biology* **3**, 564-568 (e137). (doi:10.1371/journal.pbio.0030137)

2 Masse, N. Y., Turner, G. C. & Jefferis, G. S. X. E. 2009 Olfactory information processing in *Drosophila*. *Curr. Biol.* **19**, R700–R713. (doi: 10.1016/j.cub.2009.06.026)

3 Su, C.-Y., Menuz, K. & Carlson, J. R. 2009 Olfactory perception: receptors, cells, and circuits. *Cell* **139**, 45-59. (doi:10.1016/j.cell.2009.09.015)

4 Murthy, V. N. 2011 Olfactory maps in the brain. *Annu. Rev. Neurosc.* **34**, 233-258. (doi:10.1146/annurev-neuro-061010-113738)

5 White, C. S., Lambert, D. M. & Foster, S. P. 1994 Chemical signals and the recognition concept. In *Speciation and the recognition concept: theory and application* (eds. D. M. Lambert & H. Spencer), pp. 301-326. Baltimore: John Hopkins University Press.

6 Smadja, C. & Butlin, R. K. 2009 On the scent of speciation: the chemosensory system and its role in premating isolation. *Heredity* **102**, 77-97. (doi:10.1038/hdy.2008.55)

7 Mendelson, T. C. & Shaw, K. L. 2012 The (mis)concept of species recognition. Tr. Ecol. Evol. **27**, 421-427. (doi:10.1016/j.tree.2012.04.001)

8 Maan, M. E. & Seehausen, O. 2011 Ecology, sexual selection and speciation. *Ecol. Lett.* **14**, 591-602. (doi:10.1111/j.1461-0248.2011.01606.x)

9 Servedio, M. R., Van Doorn, G. S., Kopp, M., Frame, A. M. & Nosil, P. 2011 Magic traits in speciation: 'magic' but not rare? *Tr. Ecol. Evol.* **26**, 389-397. (doi:10.1016/j.tree.2011.04.005)

10 Merrill, R. M., Wallbank, R. W. R., Bull, V., Salazar, P. C. A., Mallet, J., Stevens, M. & Jiggins, C. D. 2012 Disruptive ecological selection on a mating cue. *Proc. R. Soc. B* **279**, 4907-4913. (doi:10.1098/rspb.2012.1968)

11 Fordyce, J. A. 2010 Host shifts and evolutionary radiations of butterflies. *Proc. Royal Soc. B* **277**, 3735-3743. (doi:10.1098/rspb.2010.0211)

12 Janz, N. 2011 Ehrlich and Raven revisited: mechanisms underlying codiversification of plants and enemies. *Annu. Rev. Ecol. Evol. Syst.* **42**, 71-89. (doi:10.1146/annurev-ecolsys-102710-145024)

13 Wyatt, T. D. 2003 *Pheromones and animal behaviour: communication by smell and taste*. Cambridge: Cambridge University Press.

14 Johansson, B. G. & Jones, T. M. 2007. The role of chemical communication in mate choice. *Biol. Rev.* **82**, 265-289. (doi:10.1111/j.1469-185X.2007.00009.x)

15 Landolt, P. J. & Phillips, T. W. 1997 Host plant influence on sex pheromone behaviour of phytophagous insects. *Annu. Rev. Entomol.* **42**, 371–391. (doi:10.1146/annurev.ento.42.1.371)

16 Reddy, G. V. P. & Guerrero, A. 2004 Interactions of insect pheromones and plant semiochemicals. *Trends Plant Sci*. **9**, 253-261. (doi:10.1016/j.tplants.2004.03.009)

17 Namiki, S., Iwabuchi, S. & Kanzaki, R. 2008 Representation of a mixture of pheromone and host plant odor by antennal lobe projection neurons of the silkmoth *Bombyx mori*. *J. Comp. Physiol*. A. **194**, 501-515. (doi:10.1007/s00359-008-0325-3)

18 Chaffiol A., Kropf J., Barrozo R., Gadenne C., Rospar J. P. & Anton S. 2012 Plant odour stimuli reshape pheromonal representation in neurons of the antennal lobe macroglomerular complex of a male moth. *J. Exp. Biol.* **215**, 1670-1680. (doi:10.1242/jeb.066662)

19 Deisig N., Kropf J., Vitecek S., Pevergne D., Rouyar A., Sandoz J. C., Lucas P., Gadenne C., Anton S. & Barrozo R. 2012 Differential interactions of sex pheromone and plant odour in the olfactory pathway of a male moth. *Plos One* **7(3)**, e33159. (doi:10.1371/journal.pone.0033159)

20 Galizia, C. G. & Rössler, W. 2010 Parallel olfactory system in insects: anatomy and function. *Annu. Rev. Entomol*. **55**, 399-420. (doi:10.1146/annurev-ento-112408-085442)

21 Trona, F., Anfora, G., Bengtsson, M., Witzgall, P. & Ignell, R. 2010 Coding and interaction of sex pheromone and plant volatile signals in the antennal lobe of the codling moth *Cydia pomonella*. *J. Exp. Biol.* **213**, 4291-4303. (doi:10.1242/jeb.047365)

22 Witzgall, P., Stelinski, L., Gut, L. & Thomson, D. 2008 Codling moth management and chemical ecology. *Annu. Rev. Entomol*. **53**, 503-522. (doi:10.1146/annurev.ento.53.103106.093323)

23 El-Sayed, A., Gödde, J. & Arn, H. 1999 Sprayer for quantitative application of odor stimuli. *Enviromen. Entomol*. **28**, 947-953.

24 Knight, A. L., Light, D. M. & Trimble, R. M. 2011 Identifying (E)-4,8-Dimethyl-1,3,7-nonatriene plus acetic acid as a new lure for male and female codling moth (Lepidoptera: Tortricidae). *Environ. Entomol*. **40**, 420-430. (doi:10.1603/EN10283)

25 Carlsson, M. A., Galizia, C. G. & Hansson, B. S. 2002 Spatial representation of odors in the antennal lobe of the moth *Spodoptera littoralis* (Lepidoptera: Noctuidae). *Chem. Senses* **27**, 231–244. (doi:10.1093/chemse/27.3.231)

26 Ochieng, S. A., Park, K. C. & Baker, T. C. 2002 Host plant volatiles synergize responses of sex pheromone-specific olfactory receptor neurons in male *Helicoverpa zea*. *J. Comp. Physiol. A* **188**, 325-333. (doi:10.1007/s00359-002-0308-8)

27 Pregitzer, P., Schubert, M., Breer, H., Hansson, B. S., Sachse, S. & Krieger, J. 2012 Plant odorants interfere with detection of sex pheromone signals by male *Heliothis virescens*. *Front. Cell. Neurosc.* **6**, 42. (doi: 10.3389/fncel.2012.00042)

28 Tootoonian, S. & Laurent, G. 2010 Electric times in olfaction. *Neuron* **67**, 903-905. (doi:10.1016/j.neuron.2010.09.011)

29 Witzgall, P., Ansebo, L., Yang, Z., Angeli, G., Sauphanor, B. & Bengtsson, M. 2005. Plant volatiles affect oviposition by codling moths. *Chemoecology* **15**, 77–83. (doi:10.1007/s00049-005-0295-7)

30 Witzgall, P., Proffit, M., Rozpedowska, E., Becher, P. G., Andreadis, S., Coracini, M., Lindblom, T. U. T., Ream, L. J., Hagman, A., Bengtsson, M., Kurtzman, C. P., Piskur, J. & Knight, A. 2012 "This is not an apple" - yeast mutualism in codling moth. *J. Chem. Ecol.* **38**, 949–957. (doi:10.1007/s10886-012-0158-y)

31 Ramdya, P. & Benton, R. 2010 Evolving olfactory systems on the fly. *Tr. Genetics* **26**, 307-316. (doi:10.1016/j.tig.2010.04.004)

32 Bruce, T. J. A. & Pickett, J. A. 2011 Perception of plant volatile blends by herbivorous insects – finding the right mix. *Phytochemistry* **72**, 1605-1611. (doi:10.1016/j.phytochem.2011.04.011)

33 Smadja, C. M., Canback, B., Vitalis, R., Gautier, M., Ferrari, J., Zhou, J. J. & Butlin, R. K. 2012 Large-scale candidate gene scan reveals the role of chemoreceptor genes in host plant sepcialization an speciation in the pea aphid. *Evolution* **66**, 2723-2738. (doi:10.1111/j.1558-5646.2012.01612.x)

34 Bengtsson M, Bäckman A-C, Liblikas I, Ramirez MI, Borg-Karlson A-K, Ansebo L, Anderson P, Löfqvist J, Witzgall P. 2001. Plant odor analysis of apple: antennal response of codling moth females to apple volatiles during phenological development. J agr Food Chem 49:3736-3741

35 Light, D. M., Knight, A. L., Henrick, C. A., Rajapaska D., Lingren, B., Dickens, J. C., Reynolds, K. M., Buttery, R. G., Merrill, G., Roitman, J. & Campbell, B. C. 2001 A pear-derived kairomone with pheromonal potency that attracts male and female

codling moth, *Cydia pomonella* (L.). *Naturwiss.* **88**, 333-338. (doi:10.1007/s001140100243)

36 Coracini, M., Bengtsson, M., Liblikas I, Witzgall P. 2004 Attraction of codling moth males to apple volatiles. *Ent. Exp. Appl.* **110**, 1-10. (doi:10.1111/j.0013-8703.2004.00124.x)

37 Hern, A. & Dorn, S. 2004 A female-specific attractant for the codling moth, *Cydia pomonella*, from apple fruit volatiles. *Naturwiss.* **91**, 77-80. (doi:10.1007/s00114-003-0484-6)

38 Phillips, P. A. & Barnes, M. M. 1975 Host race formation among sympatric apple, walnut, and plum populations of the codling moth, *Laspeyresia pomonella*. *Ann. Entomol. Soc. Am.* **68**, 1053-1060.

39 Pashley, D. P. & Bush, G. L. 1979 The use of allozymes in studying insect movement with special reference to the codling moth, *Laspeyresia pomonella* L. (Olethreutidae). In Movement of highly mobile insects: concepts and methodology in research (eds. R. L. Rabb & G. G. Kennedy), pp. 333-341. North Carolina State University Press.

40 Thaler, R., Brandstätter, A., Meraner, A., Chabicovski, M., Parson, W., Zelger, R., Dalla Via, J. & Dallinger, R. 2008 Molecular phylogeny and population structure of the codling moth (*Cydia pomonella*) in Central Europe: II. AFLP analysis reflects human-aided local adaptation of a global pest species. *Mol. Phylogen. Evol.* **48**, 838-849. (doi:10.1016/j.ympev.2008.05.027)

41 Cisneros, F. H. & Barnes, M. M. 1974 Contribution to the biological and ecological characterization of apple and walnut host races of codling moth, *Laspeyresia pomonella* L.: moth longevity and oviposition capacity. *Environ. Entomol.* **3**, 402-406.

42 Piskorski, R. & Dorn, S. 2011 How the oligophage codling moth *Cydia pomonella* survives on walnut despite its secondary metabolite juglone. *J. Insect Physiol.* **57**, 744-750. (doi:10.1016/j.jinsphys.2011.02.014)

43 Witzgall, P., Chambon, J.-P., Bengtsson, M., Unelius, C. R., Appelgren, M., Makranczy, G., Muraleedharan, N., Reed, D. W., Hellrigl, K., Buser, H.-R., Hallberg, E., Bergström, G., Tóth, M., Löfstedt, C. & Löfqvist, J. 1996. Sex pheromones and attractants in the Eucosmini and Grapholitini (Lepidoptera, Tortricidae). *Chemoecology* **7**, 13-23. (doi:10.1007/BF01240633)

44 Grosjean, Y., Rytz, R., Farine, J. P., Abuin, L., Cortot, J., Jefferis, G. S. X. E. & Benton, R. 2011 An olfactory receptor for food-derived odours promotes male courtship in *Drosophila*. *Nature* **478**, 236-U123. (doi: 10.1038/nature10428)

45 Zhang, Q. H. & Schlyter, F. 2004 Olfactory recognition and behavioural avoidance of angiosperm nonhost volatiles by conifer-inhabiting bark beetles. *Agric. For. Entomol.* **6**, 1-19. (doi:10.1111/j.1461-9555.2004.00202.x)

46 Karpati, Z., Olsson, S., Hansson, B. S. & Dekker, T. 2010 Inheritance of central neuroanatomy and physiology related to pheromone preference in the male European corn borer. *BMC Evol. Biol.* **10**, 286. (doi:10.1186/1471-2148-10-286)

47 Lassance, J. M., Groot, A. T., Lienard, M. A., Antony, B., Borgwardt, C., Andersson, F., Hedenstrom, E., Heckel, D. G. & Lofstedt, C. 2010 Allelic variation in a fatty-acyl

reductase gene causes divergence in moth sex pheromones. *Nature* **466**, 486-U7. (doi:10.1038/nature09058)

48 Malausa, T., Bethenod, M. T., Bontemps, A., Bourguet, D., Cornuet, J. M. & Ponsard, S. 2005 Assortative mating in sympatric host races of the European corn borer. *Science* **308**, 258-260. (doi:10.1126/science.1107577)

49 Leppik, E. & Frerot, B. 2012 Volatile organic compounds and host-plant specialization in European corn borer E and Z pheromone races. *Chemoecol*. **22**, 119-129. (doi:10.1007/s00049-012-0104-z)

50 Witzgall, P., Kirsch, P. & Cork, A. 2010 Sex pheromones and their impact on pest management. *J. Chem. Ecol.* **36**, 80-100. (doi:10.1007/s10886-009-9737-y)

51 Cardé, R. T., Minks, A. K. 1995 Control of moth pests by mating disruption: successes and constraints. *Annu. Rev. Entomol.* **40**, 559-585. (doi:10.1146/annurev.ento.40.1.559)

52 Miller, J. R., McGhee, P. S., Siegert, P. Y., Adams, C. G., Huang, J., Grieshop, M. J., Gut, L. J. 2010 General principles of attraction and competitive attraction as revealed by large-cage studies of moths responding to sex pheromone. *Proc. Nat. Acad. Sc. USA* **107**, 22-27. (doi:10.1073/pnas.0908453107)

Figure Legends

Figure 1. Wind tunnel attraction of codling moth *C. pomonella* males (*n*=50) to the main pheromone compound codlemone (released at 0.1 pg/min) and to plant volatiles butyl hexanoate (*a*), (*E*)-ß-farnesene (*b*), pear ester (*c*), at 1 pg/min and 100 pg/min. Grey lines show attraction to 1:1000 blends of codlemone with these plant volatiles. Landings at the source are significantly increased in response to each of these 2-component blends, compared to pheromone alone (***p<0.001, two-way ANOVA; butyl hexanoate F(4,45)=45.0, ß-farnesene F(4,45)=23.75, pear ester F(4,45)=24.08). Empty circles in the codlemone response curve show significant differences between codlemone and single plant volatiles alone (p<0.0001, two-way ANOVA; butyl hexanoate F(4,45)=23.35, ß-farnesene F(4,45)=53.96, pear ester F(4,45)=20.68).

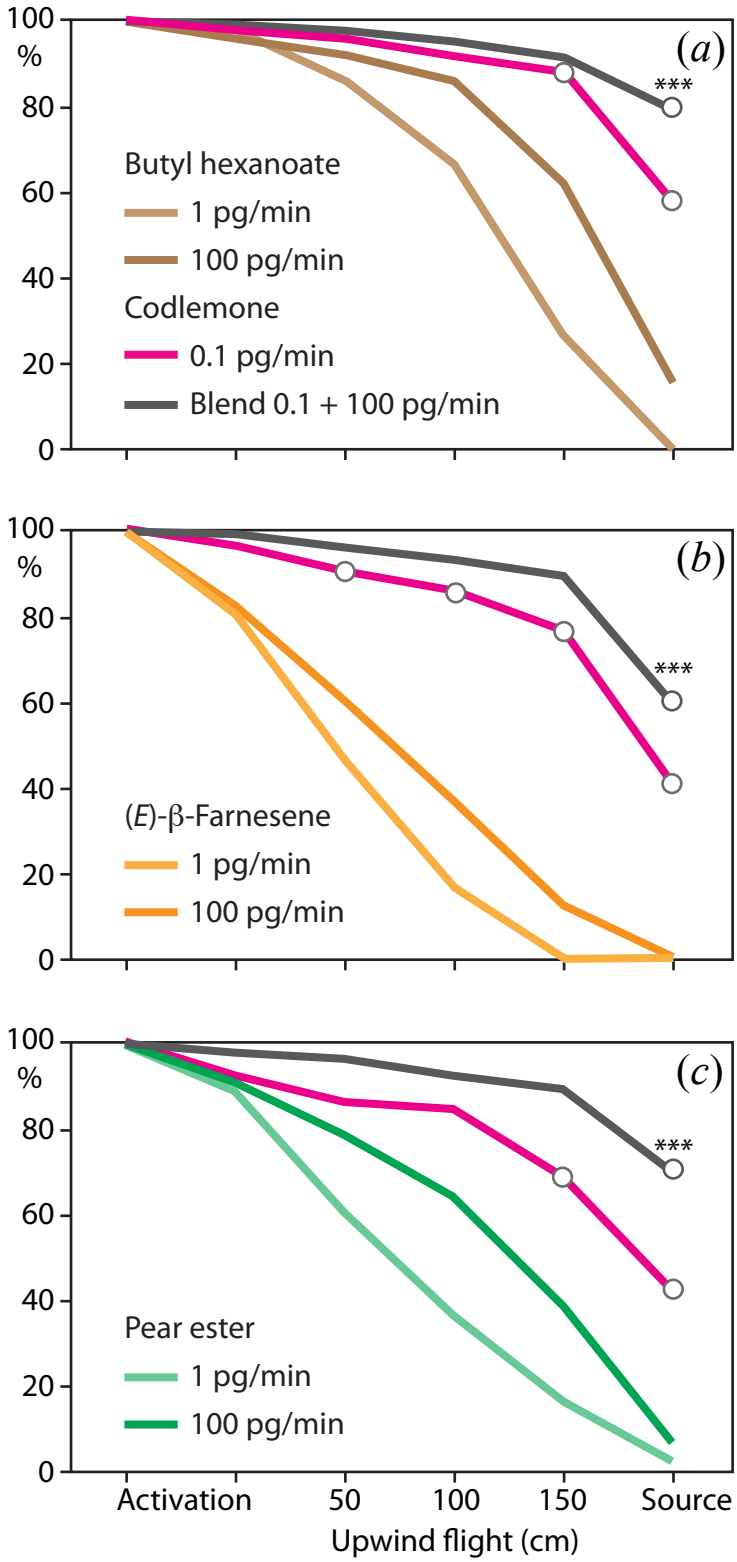
Figure 2. Calcium imaging of the codling moth male AL upon stimulation with single odorants, sex pheromone (codlemone) and three plant volatiles. Dose-response relationships of odor-evoked calcium signals, using an increasing dose of codlemone (*n*=19), pear ester (*n*=23), ß-farnesene (*n*=14) and butyl hexanoate (*n*=19) (*a*). Glomerular activation patterns in response to 10 ng codlemone (*b*), to 100 ng of pear ester (*c*), (*E*)-ß-farnesene (*d*) and butyl hexanoate (*e*), respectively and in response to the solvent (hexane) (*f*). Data points show means and standard errors (SEMs), glomeruli numbers correspond to the 3D atlas of the codling moth AL [26].

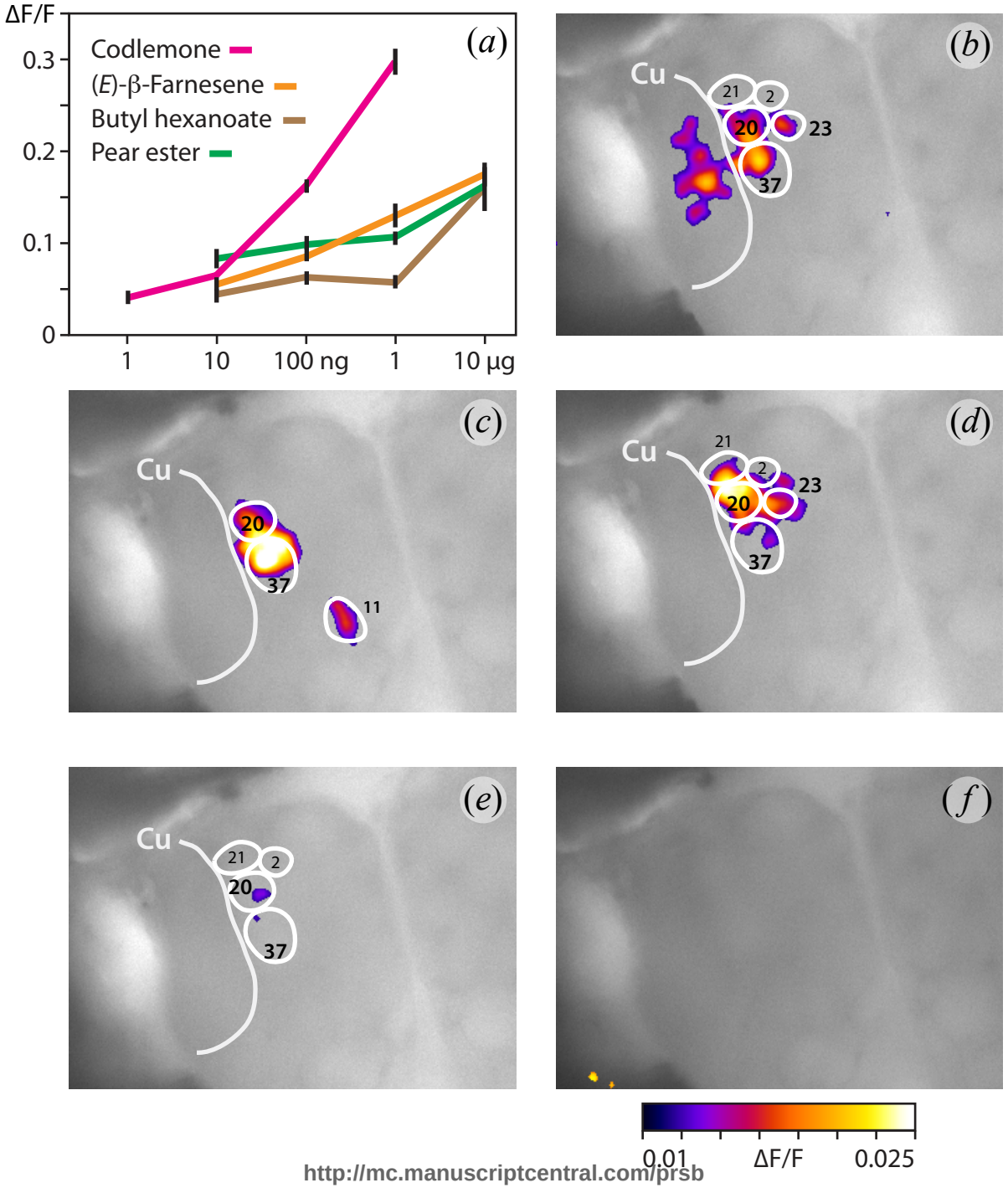
Figure 3. Calcium imaging of the codling moth male AL following stimulation with 2-component blends of sex pheromone (codlemone) and plant volatiles, butyl hexanoate,

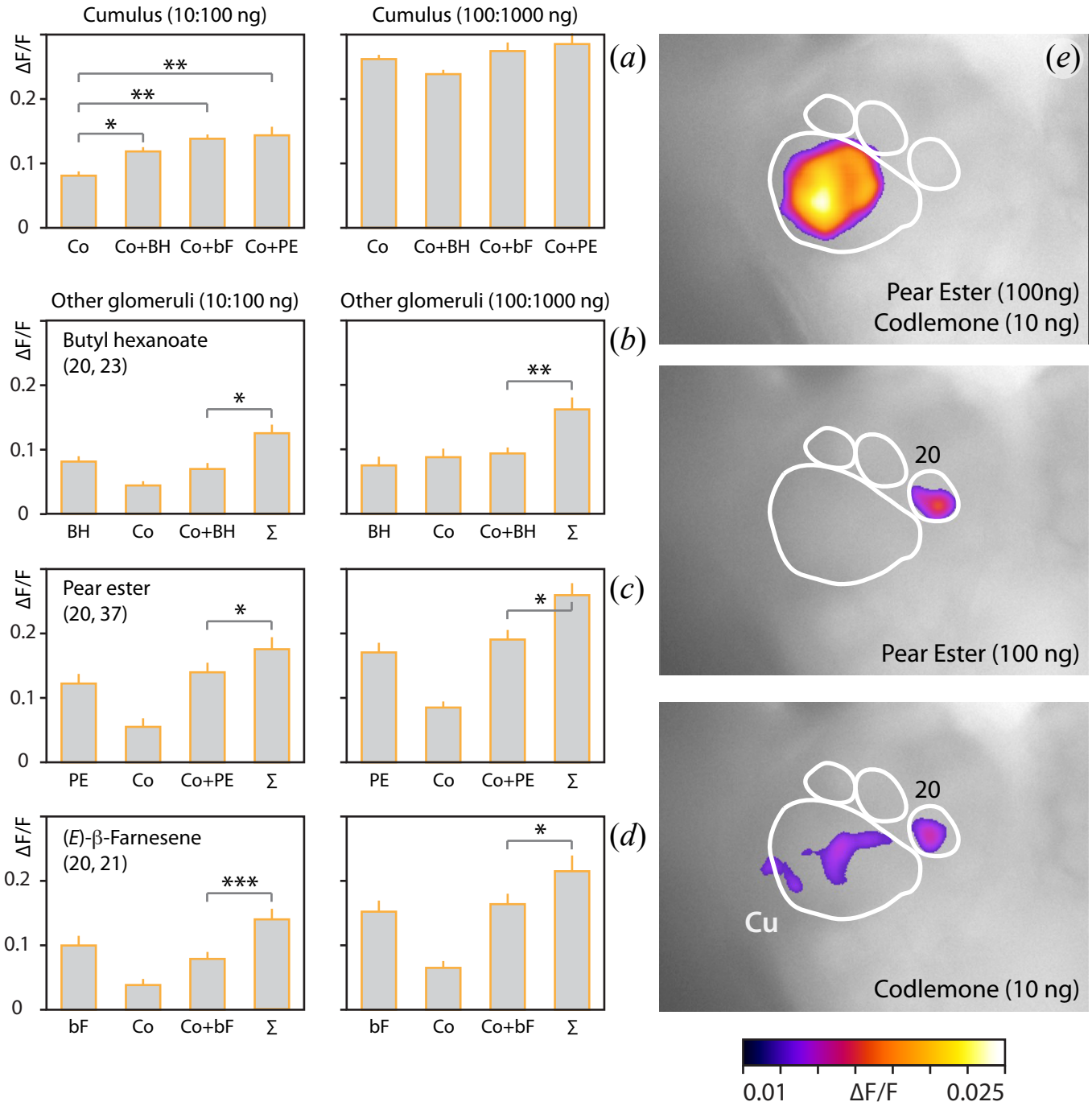
pear ester and ß-farnesene. Odour-evoked activity was measured in the cumulus (Cu) and other responding glomeruli. Response in the Cu (*a*), showing a synergistic blend interaction for 10:100 ng blends (**p*<0.05, ***p*<0.01, Kruskal-Wallis test followed by Mann-Whitney U-test with Holm-Bonferroni correction, *n*=30 males). At a higher dose, blends (100:1000 ng) were not significantly different from codlemone (*p*=0.36, Kruskal-Wallis test, *n*=30 males). Response of glomeruli outside the cumulus (*b-d*) to plant compounds, codlemone, their blends and the summed responses to single compounds (Σ): butyl hexanoate, satellite glomerulus 20 and glomerulus 23 (**p*<0.05 and ***p*<0.01, *n*=26) (*b*); pear ester, satellite glomeruli 20, 37 (**p*<0.05, *n*=30) (*c*); ß-farnesene, satellite glomeruli 20, 21 (****p*<0.001 and *p<0.05, one-sided t-test, *n*=31) (*d*). Bars show the standard error of the mean (SEM). Representative recording of codlemone, pear ester and their blend (*e*). Glomeruli numbers correspond to the atlas of codling moth AL [26].

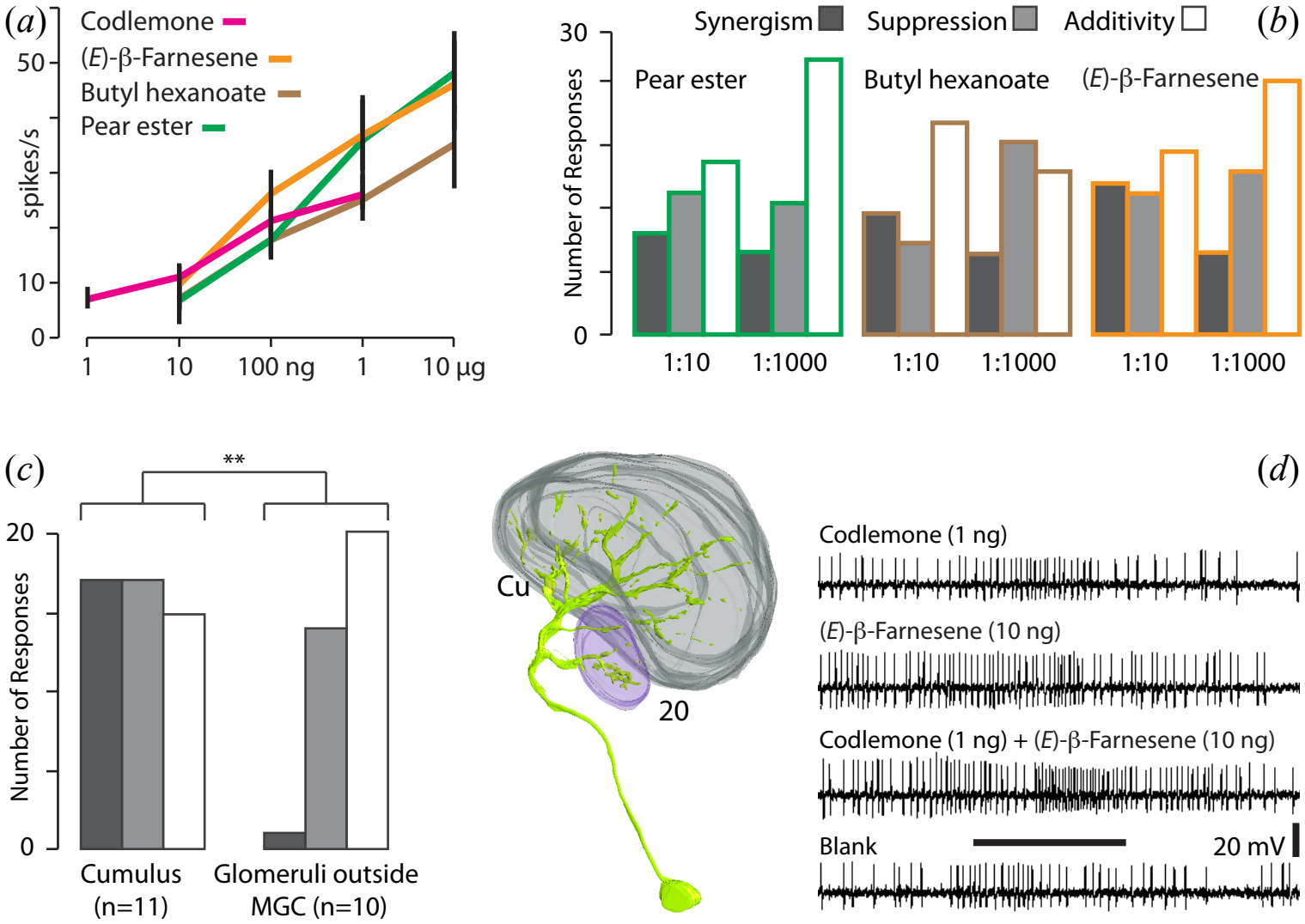
Figure 4. Responses of AL neurons to single compounds and binary blends. Intracellular recordings of AL neurons with increasing doses of codlemone (n=12), butyl hexanoate (*n*=10), pear ester (*n*=11) and ß-farnesene (*n*=12) (*a*). Histograms of synergistic, suppressive and additive responses of 69 physiologically characterized interneurons to blends of codlemone and plant volatiles (*b*). Number of synergistic, suppressive and additive responses of neurons innervating Cu and glomeruli outside the MGC (**p<0.005, Chi2-test) (*c*). 3D-reconstruction of a multiglomerular PN innervating the Cu and the satellite glomerulus 20, showing a synergistic response to a blend of codlemone and (E)-ß-farnesene. The horizontal bar shows the stimulus period (500 ms) (*d*).

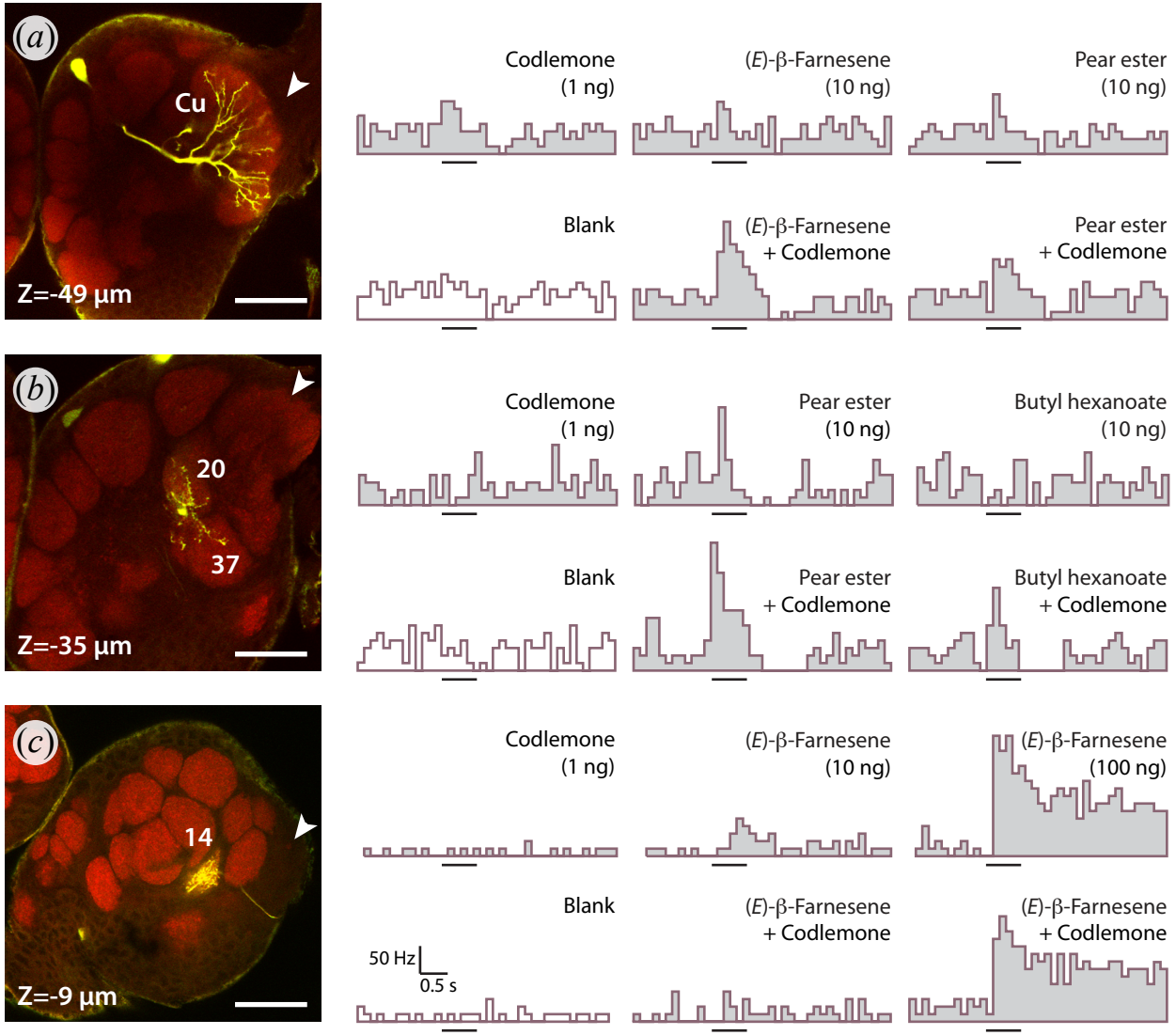
Figure 5. Single confocal sections and spike frequency histograms (spikes/s) of physiologically and morphologically characterized PNs in the codling moth male AL. Synergistic responses of a PN innervating the Cu to blends of codlemone with pear ester and ß-farnesene (*a*). Synergistic responses of a multiglomerular PN, innervating the satellite glomeruli 20 and 37, to blends of codlemone with pear ester and butyl hexanoate (*b*). Suppressive responses of a PN innervating the glomerulus 14, to a blend of codlemone and (*E*)-ß-farnesene at different blend ratios (*c*). Confocal sections: entrance of the antennal nerve (arrowheads), depth from anterior side of the AL (Z), scale bars (50 µm), glomeruli numbers correspond to the 3D AL atlas [Trona 2010]. Histograms: stimulus period (bars, 500 ms).


100
%
80
60
40
20
0
(a)
***
Butyl hexanoate
1 pg/min
100 pg/min
Codlemone
0.1 pg/min
Blend 0.1 + 100 pg/min
(b)
***
(E)-β-Farnesene
1 pg/min
100 pg/min
(c)
***
Pear ester
1 pg/min
100 pg/min
Activation
50
100
150
Source
Upwind flight (cm)


ΔF/F
0.3
0.2
0.1
0
(a)
Codlemone
(E)-β-Farnesene
Butyl hexanoate
Pear ester
1
10
100 ng
1
10 µg
(b)
Cu
21
2
20
23
37
(c)
Cu
20
37
11
(d)
Cu
21
2
20
23
37
(e)
Cu
21
2
20
37
(f)
0.01
ΔF/F
0.025


Cumulus (10:100 ng)
Cumulus (100:1000 ng)
(a)
ΔF/F
0.2
0.1
0
**
**
*
Co
Co+BH
Co+bF
Co+PE
Other glomeruli (10:100 ng)
Other glomeruli (100:1000 ng)
(b)
Butyl hexanoate
(20, 23)
*
**
BH
Co
Co+BH
Σ
(c)
Pear ester
(20, 37)
*
*
PE
Co
Co+PE
Σ
(d)
(E)-β-Farnesene
(20, 21)
***
*
bF
Co
Co+bF
Σ
(e)
Pear Ester (100ng)
Codlemone (10 ng)
20
Pear Ester (100 ng)
20
Cu
Codlemone (10 ng)
0.01
ΔF/F
0.025


(a)
Codlemone
(E)-β-Farnesene
Butyl hexanoate
Pear ester
spikes/s
50
10
0
1
10
100 ng
1
10 µg
(b)
Synergism
Suppression
Additivity
Number of Responses
30
0
Pear ester
Butyl hexanoate
(E)-β-Farnesene
1:10
1:1000
1:10
1:1000
1:10
1:1000
(c)
**
Number of Responses
20
0
Cumulus
(n=11)
Glomeruli outside
MGC (n=10)
Cu
20
(d)
Codlemone (1 ng)
(E)-β-Farnesene (10 ng)
Codlemone (1 ng) + (E)-β-Farnesene (10 ng)
Blank
20 mV


(a)
Cu
Z=-49 µm
Codlemone (1 ng)
(E)-β-Farnesene (10 ng)
Pear ester (10 ng)
Blank
(E)-β-Farnesene + Codlemone
Pear ester + Codlemone
(b)
20
37
Z=-35 µm
Codlemone (1 ng)
Pear ester (10 ng)
Butyl hexanoate (10 ng)
Blank
Pear ester + Codlemone
Butyl hexanoate + Codlemone
(c)
14
Z=-9 µm
Codlemone (1 ng)
(E)-β-Farnesene (10 ng)
(E)-β-Farnesene (100 ng)
Blank
(E)-β-Farnesene + Codlemone
(E)-β-Farnesene + Codlemone
50 Hz
0.5 s