

SHORT COMMUNICATION

The neonicotinoid clothianidin interferes with navigation of the solitary bee *Osmia cornuta* in a laboratory test

Nanxiang Jin^{1,*}, Simon Klein^{1,2,3,*}, Fabian Leimig¹, Gabriela Bischoff⁴ and Randolph Menzel^{1,‡}

ABSTRACT

Pollinating insects provide a vital ecosystem service to crops and wild plants. Exposure to low doses of neonicotinoid insecticides has sub-lethal effects on social pollinators such as bumblebees and honeybees, disturbing their navigation and interfering with their development. Solitary Hymenoptera are also very important ecosystem service providers, but the sub-lethal effects of neonicotinoids have not yet been studied well in those animals. We analyzed the ability of walking *Osmia* to remember a feeding place in a small environment and found that *Osmia* remembers the feeding place well after 4 days of training. Uptake of field-realistic amounts of the neonicotinoid clothianidin (0.76 ng per bee) altered the animals' sensory responses to the visual environment and interfered with the retrieval of navigational memory. We conclude that the neonicotinoid clothianidin compromises visual guidance and the use of navigational memory in the solitary bee *Osmia cornuta*.

KEY WORDS: Clothianidin, Neonicotinoid, Memory retrieval, *Osmia cornuta*, Learning, Navigation, Arena experiment

INTRODUCTION

Pollinating insects contribute significantly to agricultural productivity and solitary bees play a key role in the global pollination market (Garibaldi et al., 2013; Klein et al., 2007). The prevalent use of pesticides in crop protection is suspected of posing a threat to pollinating insects in agricultural landscapes (Carreck, 2015; van der Sluijs et al., 2013). Sub-lethal doses compromise memory and learning, foraging, homing behaviour, colony development and reproductive output (Desneux et al., 2007; Godfray et al., 2014; Kevan and Menzel, 2012). The effects of sub-lethal doses of neonicotinoids on solitary bees have not yet been studied in depth, with only few reports emphasizing a negative impact on, for example, larval survival rate (Tesoriero et al., 2003), foraging behaviour (Gels et al., 2002; Mommaerts et al., 2010) and species composition at the community level (Blacquièrre et al., 2012; Brittain et al., 2010).

Here, we focus on the effect of clothianidin on navigation of *Osmia cornuta* in a laboratory test. Like social bees, *Osmia* needs to return to the nest to supply their larvae with food, and to select feeding sites in the most efficient manner. Our laboratory test

requires walking *Osmia* to locate a feeding site in a small arena by visual cues at the feeding site and extra arena cues, the panorama. We show that the use of the acquired visual memory is compromised by the uptake of clothianidin.

RESULTS AND DISCUSSION

Osmia bees were trained to find a fixed feeding site in the arena using a blue local cue and visual patterns at the panorama. Naive and trained *Osmia* bees explore the arena but have a tendency for walking along the border of the arena. We, therefore, excluded trajectories within areas up to 2 cm along the vertical frame, the border of the arena. Since we use the trajectories as measures of the search behaviour, we excluded resting times – periods of 6 s of not walking. This procedure does not induce a bias in the comparison between naive control bees and treated bees because resting times did not differ between these two groups. These procedures led to summed periods of active time in each of the four quadrants as a measure of spatial exploration. Representative examples of walking trajectories are presented in supplementary material Movies 1–4. Naive control bees did not prefer any of the four quadrants, but trained control bees spent more active time in the quadrant of the local cue, indicating that they recognized and learned the local cue as the rewarding site (Fig. 1A,B).

In the dissociation test (see Materials and methods), the trained control bees walked from the local cue to the panorama location more frequently than naive control bees did (Fig. 2), indicating that they also remembered the panorama-related location, although the local cue overshadowed the selection of the panorama location.

Naive pesticide-treated bees spent significantly more time in quadrants 1 and 2 than naive control bees (supplementary material Fig. S1A), indicating that they responded differently to cue and/or panorama. We next asked whether the locomotor behaviour changed in treated animals and found no difference in walking speed between control and treated animals, but there was a difference in the straightness of their walks (supplementary material Fig. S2). This difference, however, does not cause a preference of treated animals for quadrants 1 and 2. Most importantly, trained treated animals did not distribute their active times equally in the four quadrants (Fig. 3). In particular, the quadrant with the local cue (Q2) was not preferred over the other quadrants, either in naive or trained animals. This result shows that clothianidin interferes with the retrieval of memory for the learned guiding features in the arena, the local cue and the panorama. Thus clothianidin treatment leads to a block of memory retrieval for cues guiding *Osmia* to the location of the feeding site, the local cue and the panorama.

Laboratory tests of spatial learning in animals have a long tradition in behavioural biology (Jacobs and Menzel, 2014; Tolman, 1948; Wiener et al., 2011). The test conditions in our experiments exposed the animal to a local cue and to extra-maze cues that either in addition or alone signalled a location to the

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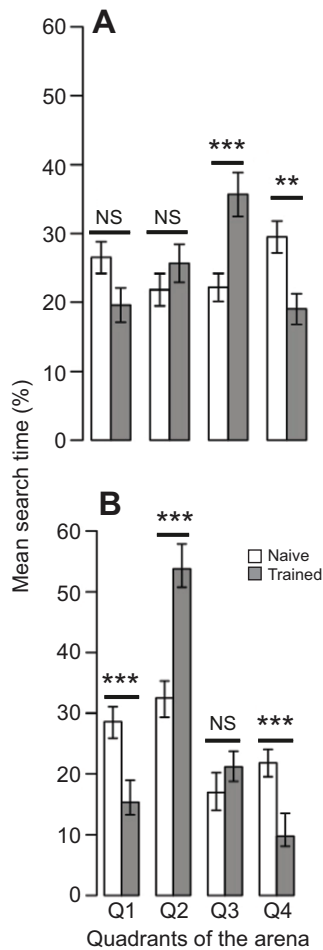


Fig. 1. Distribution of summed and normalized active times in the arena during tests of naive and trained bees. The feeding site on the local cue was located in Q2. (A) Panorama and local cue are co-localized. (B) Panorama and local cue are dissociated by a rotation of 90 deg relative to each other during the testing. The ordinate gives the mean percentage of summed and normalized active time. The Friedman test for repeated measurements was used to test the learning effect of training to the feeding site (NS, not significant). Naive control group: $\chi^2=7.59$, $P=0.055$; trained control group: $\chi^2=19.14$, $P<0.001$; naive treated group: $\chi^2=39.27$, $P<0.001$; trained treated group: $\chi^2=79.59$, $P<0.001$. ** $P<0.005$; *** $P<0.0015$.

animal. *Osmia*, like bumblebees in a similar test situation, learned both the cue and the panorama-related location (Jin et al., 2014). This rather simple training and test procedure allows the study of basic forms of navigation under strictly controlled conditions. *Osmia* is compromised in its ability to use this basic form of navigational memory after exposure to a neonicotinoid. Neonicotinoids act as agonists to nicotinic acetylcholine receptors (nAChRs) in the insect brain, leading to lasting overexcitation followed by a block of synaptic transmission (Matsuda et al., 2001). nAChRs are particularly frequent in central sensory projections and higher-order interneurons, for example, in the mushroom body. It is thus likely that high-order sensory integration, learning, memory formation and memory retrieval may be affected by neonicotinoids.

Navigation of honeybees under natural conditions was found to be disturbed after exposure to sub-lethal doses of different neonicotinoids (Henry and Decourtye, 2013), although their sensory and motor performance, as well as their ability to use the sun compass for navigation, was not affected (Fischer et al., 2014).

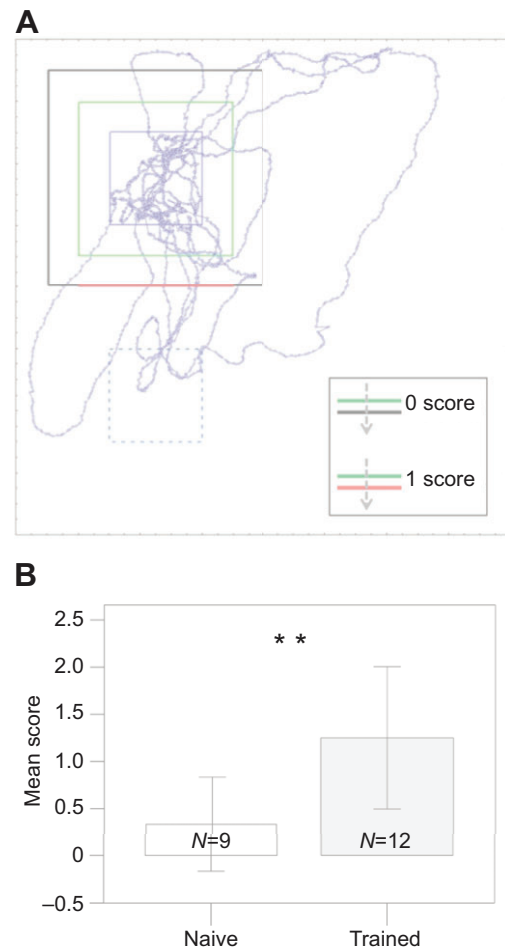


Fig. 2. Directional components of outbound trajectories from the local cue during the dissociation test in control bees. (A) Local cue and panorama locations are dissociated by 90 deg. The lines around the local cue (blue solid line square) define an inner box (green, length of sides: 4 cm) and an outer box (black and red lines, length of sides: 13.8 cm; the length proportion of red:black is 5:23). The blue dotted box marks the feeding place indicated by the panorama. Trajectories crossing first the green lines and then the black or red lines were counted as departing from the local cue. Those crossing the red line were given a score of 1 because they indicate a departure from the local cue area towards the panorama location. Trajectories crossing the black lines scored 0. Only the first and second departures of each bee were assessed. Thus the score of a single bee could be 0, 1 or 2. (B) Mean departure scores for the dissociation of 90 deg. Since animals from the naive and the trained groups are different, the two groups are independent of each other. Therefore, we applied an independent samples *t*-test with the null hypotheses that the panorama is not guiding the trained animals to the feeding site, and therefore the probabilities for naive and trained animals to move from the local cue to the panorama related location are the same. The null hypothesis can be rejected (** $P<0.01$, error bars show s.d.). The number of animals tested is given in the columns.

In contrast, naive clothianidin-treated *Osmia* spent more time in a sub-region of the arena close to the tilted black stripes of the panorama and furthest away from the blue board of the local cue, indicating a possible visuomotor effect of clothianidin on spontaneous *Osmia* behaviour. Because motor performance did not change, we interpreted the clothianidin effect on naive *Osmia* as a modulation of visual perception that was not seen in the honeybee, possibly because of less well-controlled conditions.

Our study documents two major differences between the control group and the treated group. First, naive treated animals and trained

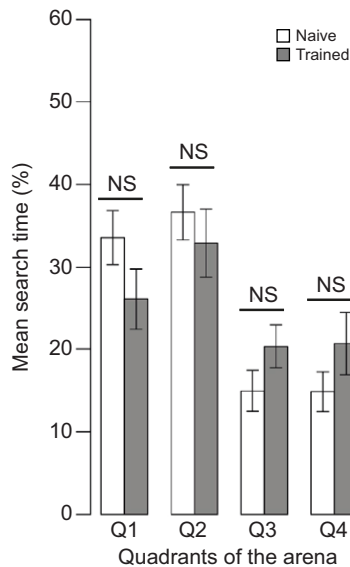


Fig. 3. Distribution of cumulative active time in treated bees. Open columns give the summed active time for naive treated animals, and grey columns trained treated animals. The Friedman test for repeated measurements was used to test whether the null hypothesis (no difference in the active times in naive and trained bees) applies (NS, not significant). The Friedman test for repeated measurements (with minutes as repeated measurements) was used to test the difference in each quadrant for a particular group. Naive control group: $\chi^2=7.59$, $P=0.055$; trained control group: $\chi^2=19.14$, $P<0.001$; naive treated group: $\chi^2=39.27$, $P<0.001$; trained treated group: $\chi^2=79.59$, $P<0.001$. Error bars show s.d.

treated animals do not distribute their search trajectories evenly across the arena but preferred a sub-region not including the blue cardboard as a local cue (supplementary material Fig. S1). Second, trained treated animals were unable to use the memory they had acquired during training. The first effect indicates that clothianidin treatment alters the sensory response to environmental cues arising from extra-maze signals. This effect is particularly important because the panorama-related cues allow the animal to localize the feeding place without the local cue. Although we cannot yet identify whether particular panorama signals become either more or less attractive following clothianidin treatment, it is obvious that uptake of this neonicotinoid alters the animals' detection and/or evaluation of visual signals. The second effect documents that the clothianidin-treated animals were not able to find the learned quadrant with the feeding site.

The clothianidin dose used in our study ($0.76 \text{ ng animal}^{-1}$) lies within the range of expected uptake from treated oilseed crops. Residue intake has been estimated to range from 4.27 to $13.65 \text{ ng per bee day}^{-1}$ (Authority, 2013). Similar doses during chronic exposure to a different neonicotinoid (imidacloprid) were used by Tasei et al. (2000), who found in bumblebees reduced survival of workers and less brood production. Rundlöf et al. (2015) found $6.7\text{--}16 \text{ ng ml}^{-1}$ clothianidin in the nectar store of honeybees foraging in oil rape fields that grow from seeds coated with clothianidin. The respective values for bumble bees are $1.4\text{--}14 \text{ ng ml}^{-1}$. One can estimate that a honeybee or a bumble bee will usually collect about $50 \mu\text{l}$ of nectar on one foraging trip. Thus, each honeybee takes up about $0.335\text{--}0.8 \text{ ng}$ clothianidin during one foraging trip (bumblebee $0.07\text{--}0.7 \text{ ng}$). Depending on foraging time and distance travelled in consecutive foraging trips, a considerable amount of the collected clothianidin will be taken up by the body of the bee. We fed each *Osmia* bee 0.76 ng

clothianidin, which was a dose close to what can be expected from these data.

These results document that clothianidin, taken up at a concentration lower than 1 ng per bee , blocks the retrieval of memory necessary for navigating towards a learned location, corroborating findings from previous studies on solitary bees (Abbott et al., 2008) and social bees (Fischer et al., 2014; Schneider et al., 2012). Further tests are needed to determine the dose-dependent effects of neonicotinoids on learning, memory formation and memory retrieval in the context of navigation in order to evaluate the sensitivity of solitary bee species to neonicotinoid uptake.

MATERIALS AND METHODS

Animals

Osmia cornuta (Latreille 1805) emerged from the pupae during early spring (March to May). The pupae were purchased from Mike Herrmann (Mauerbienenzucht, Konstanz, Germany) and stored in the refrigerator at 4°C until 1 day before use. Virgin females were trained 1 day after emerging from pupation. We cut the right wing of each bee in order to prevent her from flying. Four groups of animals were tested: naive bees without exposure to clothianidin ($N=20$, naive control); trained bees without exposure to clothianidin ($N=12$, trained control); naive animals treated with clothianidin ($N=10$, naive treated), and trained bees treated with clothianidin ($N=10$, trained treated).

Experimental setup, training and tests

The animals were trained and tested in an arena (Fig. 4) and video recorded (15 fps) using a web camera inserted through a hole in the centre of the ceiling of the arena. Exploratory behaviour can be stimulated with evenly distributed odour in the air space above the arena. We placed a piece of paper soaked with 50 litres of liquid citral at the centre of the ceiling. All structures inside the arena were assembled symmetrically, and therefore no geometrical cues were available to the bees other than the panorama (simple patterns on inner walls, see Fig. 4). The animals were trained during an exploratory period during which they were fed three times diluted honey (1:1 honey:water based on volume) on a $5\times 5 \text{ cm}$ blue cardboard paper (local cue). Training time was different for different animals (2–15 min) depending on how long it took them to find the reward. Training sessions of each animal were performed at the same time of day for four consecutive days. Note that the odour of the honey did not interfere with the test procedure (see below). On the fifth day, the trained bees (control or treated) were tested in one of the following two ways: (1) both local cue and panorama were rotated 90 deg clockwise (Fig. 4C, the direction of 90 deg rotation was randomly chosen); (2) The local cue was rotated 180 deg while the panorama was rotated 90 deg clockwise (Fig. 4D). In both tests, the honey water was removed, and the ground cardboard was gently moved over to the test ground without moving the plastic frame. In this way, any putative odour cues were removed, and the search behaviour was guided only by visual cues. The starting place was randomly chosen from any quadrant where the local cue was not located. Each test lasted for 15 min. Naive animals (control and treated) were not trained and were tested on the day they emerged.

Pesticide preparation

The clothianidin standard (Sigma-Aldrich, Hamburg, Germany) was diluted in acetone, mixed with tap water leading to a stock solution (SS) of a concentration of 135.77 ppm, and further diluted in two steps to obtain the final concentration in the feeding solution (FS) of 0.076 ppm ($0.076 \text{ ng } \mu\text{l}^{-1}$). The concentrations of SS and the first step of dilution of FS were checked with LC-MS/MS (see below).

Clothianidin treatment

Preliminary experiments showed that administration of 1.25 ng clothianidin per animal leads to a mortality rate of 70% within 2 h of intake. We therefore reduced the concentration to $0.76 \text{ ng per animal}$. Furthermore, we observed

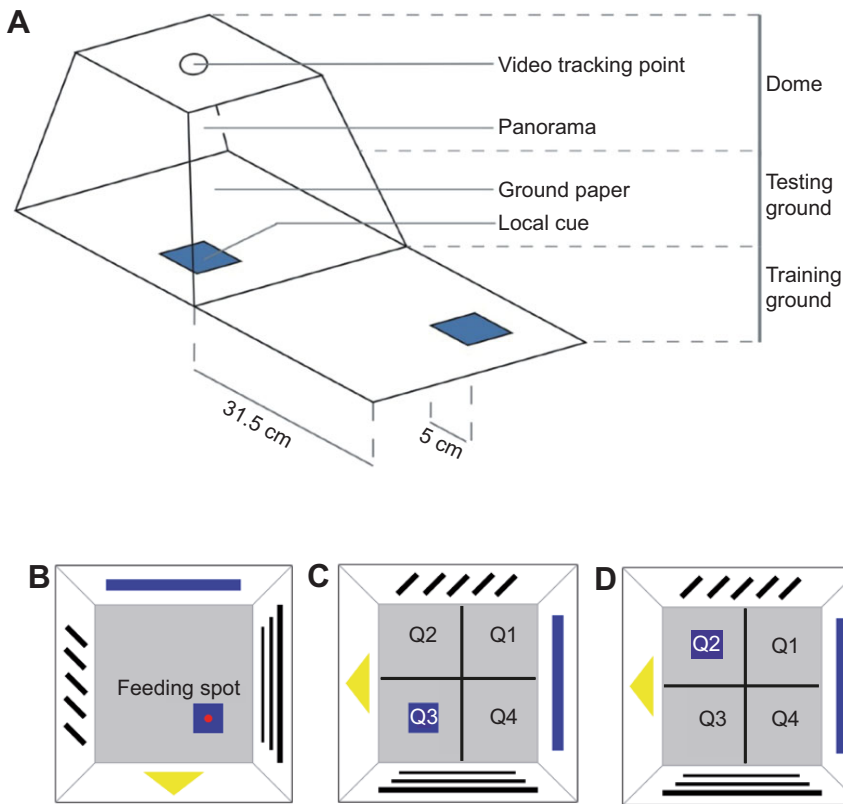


Fig. 4. Experimental setup. (A) The ground of the arena consists of a plastic board on which a grey cardboard paper can be moved across the ground. A transparent plastic frame (31.5 cm×31.5 cm×10 cm) confines the range of the arena ground. The local cue (blue board of 5×5 cm) marks the reward in its centre. The walking tracks of the animals were recorded using a camera on the top of the dome. (B) Bird's eye view of the arena (local cue on the ground and panorama patterns on walls) during training. The red spot indicates the location of the feeding spot, the opening of a transparent plastic tube. (C,D) Orientation of the ground paper and the panorama for the tests. In C, the ground paper and the panorama are rotated by 90 deg. In D, the local cue is rotated 180 deg while the panorama is rotated 90 deg clockwise (dissociation test). The feeding capillary was removed. These figures also show the division of the arena into 4 quadrants (Q1 to Q4) for the purpose of the statistical analyses.

that naive animals behaved normally in the arena 60 min after uptake of 10 μ l clothianidin in diluted honey solution (see supplementary material Fig S2A,B, 'control' columns). In the tests of treated naive animals, the animals were fed with 0.76 ng clothianidin per bee 1 h after they were caught and then incubated for 1 h before the test. In the retention test after 4 days of training, *Osmia* were fed with 0.76 ng per bee clothianidin immediately after the last training and 1 h before the test on the 5th day. All treated animals were kept in a dark wooden box after uptake of the pesticide for pesticide incubation.

A total of 22 *Osmia* bees were trained, 12 control bees were tested on the 5th day and 10 treated bees after imbibing 10 μ l of a mixture of honey-water solution and pesticide. In order to quantify the learning effect, 30 naive bees (20 controls, 10 treated) were tested without training.

LC-MS/MS

The system used was a Shimadzu LC-20A Prominence HPLC coupled to a triple quadrupole mass spectrometer AB SCIEX 4000 Q TRAP equipped with a TurboIonSpray Source (TIS/ESI). The chromatographic separation was performed on a Kinetex C₁₈ column (50×3 mm, 2.6 μ m diameter) with a KrudKratzcher Ultra pre-column, both from Phenomenex. The column thermostat temperature was set to 40°C and the autosampler temperature was set to 15°C. The injection volume was 5 μ l. Samples were analyzed with the mobile phases (A) methanol:water (90:10) and (B) water, both with 0.1% acetic acid and 5 mM ammonium formate. The flow rate was 0.8 ml min⁻¹. The gradient programme was as follows: from 0 to 1 min, linear gradient from 10% to 100% (A), from 1.0 to 2.5 min hold at 100% (A), from 2.5 to 2.51 min linear gradient from 100% to 10% (A), from 2.51 to 3.8 min hold at 10% (A).

Electrospray ionization was performed in the positive mode. The mass spectrometric parameters were: curtain gas: 20 psi; collision gas: high; ionspray voltage: +5500 V; source temperature: 550°C; nebulizer gas pressure: 70 psi; turbo gas pressure: 50 psi. Clothianidin was characterized by its retention time and three multiple reaction monitoring (MRM) transitions. For quantification (internal standard method) six calibration points were prepared with concentrations of 1, 5, 10, 25, 50 and 100 μ g μ l⁻¹ clothianidin in methanol:water (1:1).

Statistical analysis

The normality of the distribution of the distance travelled was evaluated by the Shapiro test. The differences were tested by a one-way ANOVA. The trajectories of walking in the tests were analysed with respect to the active times spent in one of four quadrants (Figs 1 and 3). The summed active times spent in each quadrant was calculated during the first four minutes of active time. Since the values were not normally distributed (Shapiro test, $P < 0.01$) the Friedman rank sum test was applied. All statistical analyses were performed with RStudio (0.98.507) for R v3.0.2. The Friedman test for repeated measurement was provided using the package muStat. Setout directions were analysed with the independent *t*-test (Fig. 2).

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Competing interests

The authors declare no competing or financial interests.

Author contributions

R.M. and N.J. built the arena setup; S.K., N.J. and R.M. designed the experimental procedure and wrote the manuscript; S.K., F.L. and N.J. ran the behavioural experiments; N.J. wrote the R program scripts to extract and organize the data from video recordings; S.K. and N.J. ran the statistical tests; G.B. applied the LC-MS/MS analysis.

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Supplementary material

Supplementary material available online at <http://jeb.biologists.org/lookup/suppl/doi:10.1242/jeb.123612/-DC1>

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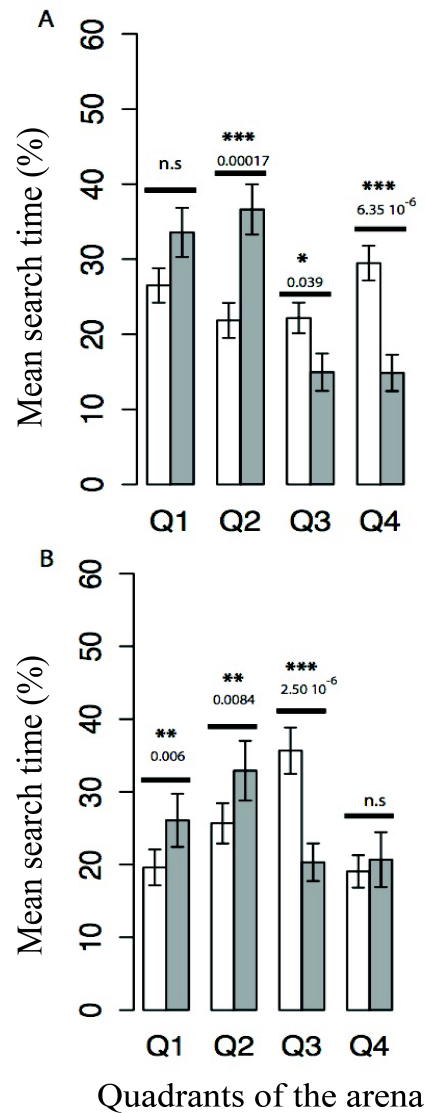


Fig. S1. Comparison of cumulative active time in untreated control animals and Clothianidin treated animals during the test in which local cue and panorama related location are colocalized. (A) Naïve bees, (B) trained bees. The open bars show the values for untreated control animals, the dark bars those of Clothianidin treated animals. The ordinate gives the mean percentage of active time. Friedman test for repeated measurements was applied to test the difference between the two groups for each quadrant. n.s.: not significant. Friedman test for repeated measurements (with minutes as repeated measurements) was used to test the difference in each quadrant for a particular group. Naïve control group: chi-square = 7.59, p-value = 0.055, trained control group: chi-square = 19.14, p-value < 0.001, naïve treated group: chi-square = 39.27, p-value < 0.001, trained treated group: chi-square = 79.59, p-value < 0.001.

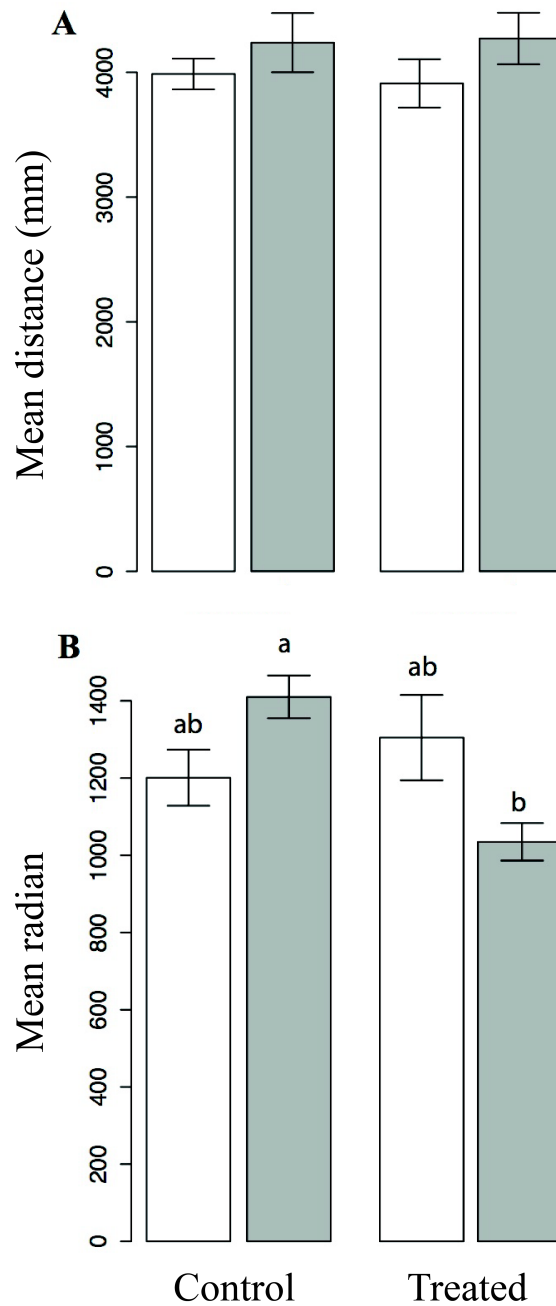
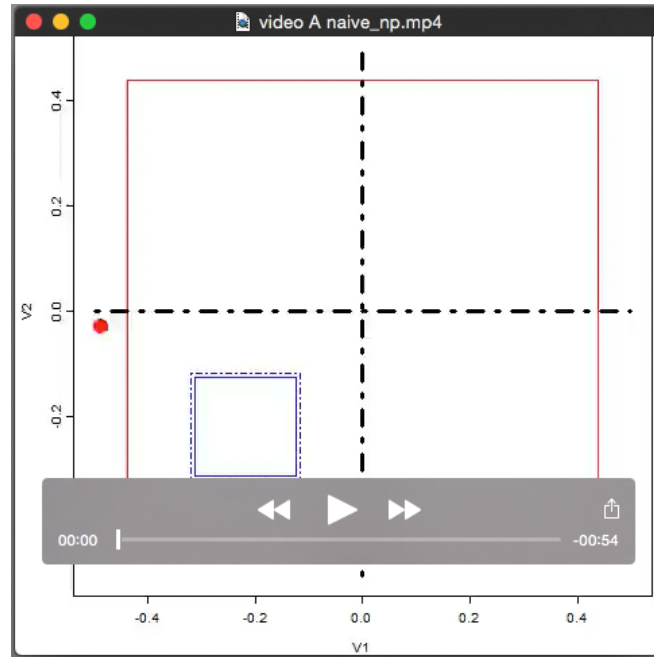
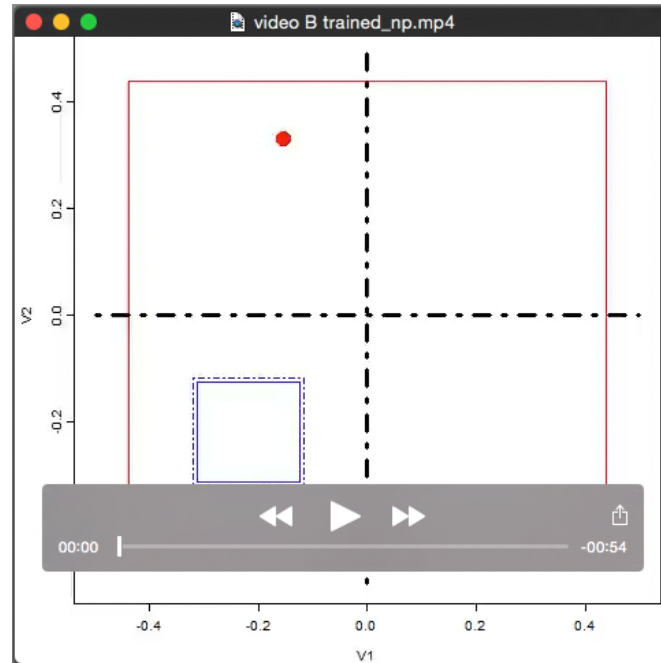


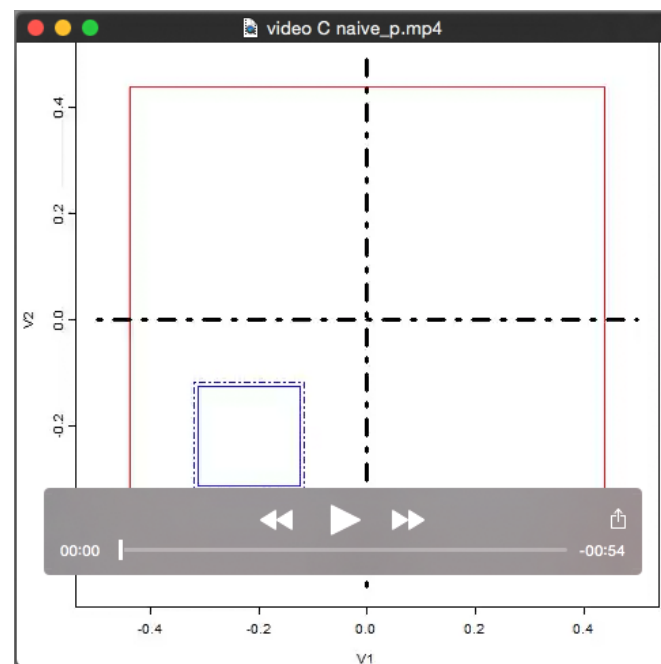
Fig. S2. Comparison of walking characteristics in trained animals during memory retrieval tests. Open bars show the values for naïve animals, dark bars those of trained animals. (A) Mean of the cumulative distance walked during the first two active minutes by animals of each groups (control, treated). Y-axis: distance traveled in mm. Shapiro test >0.01 , the data follow a normal law. Two ways ANOVA results: $F=0.872$, $p\text{-value}=0.46$. The differences are not significant. (B) Mean of the cumulating changing angles of walking trajectories calculated for the first 2 minutes of each control or treated bee (y-axis in radian). Two ways ANOVA results: $F=4.053$, $p\text{-value}: 0.0103$. Statistically significant differences are indicated by different letters (a,b).



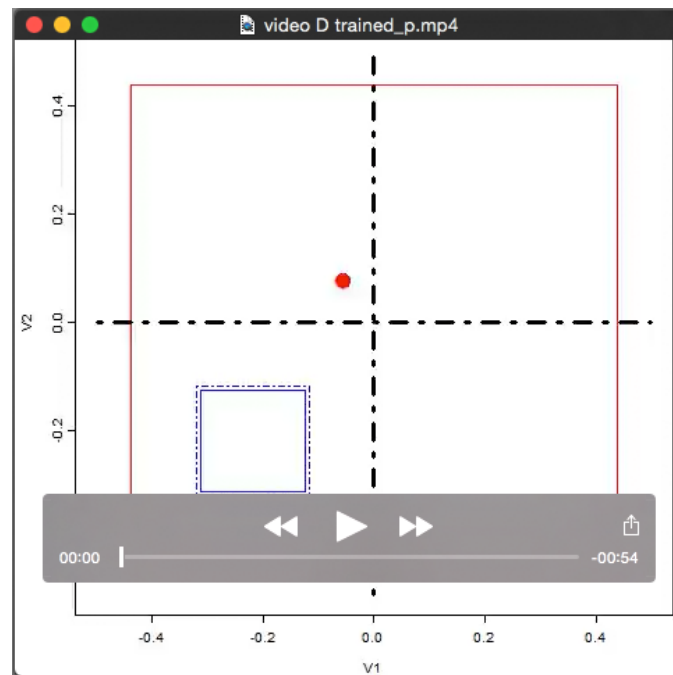
Movie 1. Naïve bee in a control testing condition. Movies show tracks of bees during the first 3 min of the bright phase II of the test. The black hatched cross separates the 4 quadrants, respectively from right to left, from upper part to the lower part: Q2, Q1, Q3, Q4. The red square indicates the limit of the considered thigmotactic behavior, close to the vertical frame (outside the red square). The blue cue is represented by the blue square in the Q3 quadrant.



Movie 2. Tracks of a trained bee in a control testing condition.



Movie 3. Tracks of a naïve bee that has licked pesticide 60 min before the test.



Movie 4. Tracks of a trained bee that has licked pesticide 60 min before the test.