Honeybees generalize among pollen scents from plants flowering in the same seasonal period.

Ana Laura Pietrantuono[1,2*], Fabrice Requier[1,3], Valeria Fernández- Arhex[1,2], Josefina Winter[4], Guillermo Huerta[2] and Fernando Guerrieri[5]

[1] CONICET- CCT Patagonia Norte. Av. de los Pioneros 2350, San Carlos de Bariloche, (8400), Río Negro- Argentina.

[2] IFAB-Investigaciones Forestales y Agropecuarias Bariloche, INTA EEA-Bariloche. Modesta Victoria 4450, CC 277. San Carlos de Bariloche (8400), Río Negro- Argentina.

[3] Evolution Génome Comportement et Ecologie, CNRS, IRD, Université Paris-Sud, Université Paris-Saclay, Gif-sur-Yvette, 91190 Paris, France.

[4] INTI-Sede Neuquén. Ruta 7 Km 5 Mercado Concentrador. Parque Industrial (8300) Neuquén- Argentina.

[5] IRBI- Institut de Recherche sur la Biologie de l'Insecte UMR 7261, CNRS – Université de Tours, France.

* Corresponding author: Ana Laura Pietrantuono pietrantuono.ana@inta.gob.ar

Key words: *Apis mellifera*, conditioning, palynology, proboscis extension response, similarity.

Summary statement: Honey bees' PER was conditioned using different pollen scents, then tested with novel pollen scents. Honey bees generalized the pollen scents from plants that share the same flowering period.

Abstract

When honey bees (*Apis mellifera*) feed on flowers they extend their proboscis to absorb the nectar, *i.e.* they perform the proboscis extension response (PER). The presence of pollen and/or nectar can be associated with odors, colors or visual patterns, which allows honey bees to recognize food sources in the environment. Honey bees can associate similar, though different, stimuli with the presence of food; *i.e.* honey bees discriminate and generalize among stimuli. Here, we evaluated generalization among pollen scents from six different plant species. Experiments were based on the PER conditioning protocol over two phases: (1) *Conditioning*, in which honey bees associated the scent of each pollen type with sucrose, and (2) *Test*, in which honey bees were presented with a novel scent, to evaluate generalization. Generalization was evinced by honey bees extending their proboscis to a novel scent. The level of PER increased over the course of the conditioning phase for all pollen scents. Honey bees generalized pollen from *Pyracantha coccinea* and from *Hypochaeris radicata*. These two plants have different amounts of protein and are not taxonomically related. We observed that the flowering period influences the olfactory perceptual similarity and we suggested that both pollen types may share volatile compounds that play key roles in perception. Our results highlight the importance of analyzing the implications of the generalization between pollen types of different nutritional quality. Such studies could provide valuable information for beekeepers and agricultural producers, since the generalization of a higher quality pollen can benefit hive development, increase pollination and honey production.

Introduction

Learning can be defined as a change in behavior due to an individual's experience. Indeed, behavioral plasticity is crucial for an animal, since it enables adaptation to a constantly changing environment (Giles and Rankin, 2009). In this context, the ability to both discriminate and to generalize among different stimuli is a key factor for survival, for instance, when facing changes in food availability. Discrimination allows the animal telling different stimuli apart, whilst generalization allows classifying similar, though different, stimuli into the same category (Getz and Smith, 1987; Laska et al., 1999; Gumbert, 2000; Ghirlanda and Enquist, 2003; Guerrieri et al., 2005; Robazzi Bignelli Valente Aguiar et al., 2018). The western honey bee (*Apis mellifera*, Linnaeus) represents one of the principal model organisms in the study of learning (Menzel and Erber, 1978; Menzel, 1999; 2001; Giurfa, 2003; 2007; 2015). During foraging lifetime, honey bees are confronted to different stimuli, such as floral scents, colors and textures, some of which are associated with the presence of food (*i.e.* nectar, pollen). Concretely, honey bees perceive and remember different types of stimuli (*i.e.* visual, tactile, chemical) and can associate them with other stimuli. For instance, an odor can be associated with a reward, *e.g.* sucrose solution (von Frisch, 1967; Hammer and Menzel, 1995; Tedjakumala and Giurfa, 2013; Giurfa, 2015), or with a punishment, *e.g.* an electric shock (Vergoz et al., 2007; Bos et al., 2013). Here, we investigated how honey bees generalize among scents from different pollen types (*i. e.* pollen from different plant species) and which characteristics allowed pollen types be perceived as similar by individuals. Many studies on honey bee learning have been performed observing the proboscis extension response (PER). This response occurs when honey bees land on flowers and detects the presence of nectar with their antennae. Thus, individuals associate the flower shape, color and odor with the presence of food, *i.e.* associative learning is induced. This behavior can be reproduced under laboratory conditions using harnessed honey bees that spontaneously extend their probosces when their antennae are stimulated with sucrose solution. An odor (conditioned stimulus: CS) forward-paired with the sucrose reward (unconditioned stimulus: US) becomes a predictor stimulus of reward. Thus, an association is built between both stimuli, this association is known as *PER conditioning* and has been extensively used in studies of learning for the last six decades (Takeda, 1961; Bitterman et al., 1983; Hammer and Menzel, 1995; Gerber et al., 1996; Giurfa, 2007; Avarguès-Weber et

al., 2011; Matsumoto et al., 2012). Using this methodology, honey bees have been assayed following a great variety of learning paradigms allowing researchers to unravel how they interact with their environment (Giurfa, 2003; Bos et al., 2013; Giurfa and Sandoz, 2015; Baracchi et al., 2018).

Honey bees follow a "flower constant" foraging strategy, meaning that, once an individual recognizes the flower of a certain plant species as a convenient food source, it will preferentially forage on flowers of that plant species so far those flowers are available (see Chittka et al., 1999). Honey bees collect nectar and pollen during their foraging trips. Nectar mainly provides carbohydrates, while pollen provides proteins and lipids, which constitutes the food supply for the colony (Winston, 1987; Fewell and Winston, 1992; Roulston and Cane, 2000; Requier et al., 2017). Floral nutritional resources (nectar and pollen) vary in quality and quantity among plant species (Scheiner et al., 2004; Di Pasquale et al., 2013; Vaudo et al., 2015) and in the course of the season. Therefore, honey bees forage on a wide diversity of plants to fulfill their nutritional quality needs, including in human-disturbed landscapes such as croplands (Requier et al., 2015). Honey bees discriminate among nectar types based on nutritional attributes while different types of pollen are distinguished via both gustatory and olfactory cues. For instance, several authors have shown the honey bees' ability to generalize among visual or olfactory stimuli (Wehner, 1967; 1971; Smith and Menzel, 1989; Giurfa et al., 1996; Deisig et al., 2002; 2003; Stach et al., 2004; Guerrieri et al., 2005; Benard et al., 2006; Horridge, 2009). Concerning the olfactory modality, it has been observed that honey bees are able to generalize among both pure odors (Guerrieri et al., 2005) and odor blends (Reinhard et al., 2010). Nonetheless, the criteria by which honey bees generalize among pollen types are not yet fully understood (Pernal and Currie, 2001; Cook et al., 2005; Nicolson, 2011; Ruedenauer et al., 2015; 2018; Beekman et al., 2016; Muth et al., 2016).

Under natural conditions, flowers release mixtures of volatile substances, thus producing complex and diverse odor cues. The composition of the mixture varies from one flower to another one, even among flowers of the same plant species. To identify different flowers as conspecific, a flower constant forager must be able to discriminate among flowers coexisting in the field to identify the preferred plant species (Menzel, 1985). Furthermore, a floral constant forager must be able to generalize among flowers; that means, to recognize that different flowers correspond to the preferred plant species (Free, 1963; Wright and

Schiestl, 2009). Under laboratory conditions, some studies evaluated honey bees' perceptual ability to identify resources found in nature has been evaluated (Pernal and Currie, 2001, 2002; Cook et al. 2003, 2005; Arenas and Farina, 2012; Nicholls and Hempel de Ibarra, 2017). Pollen, unlike nectar, is neither collected with the proboscis nor stored in the crop. However, it is adaptive for honey bees to estimate the quality of pollen and hence to generalize based on nutritional characteristics (Nicholls and Hempel de Ibarra, 2017). For instance, honey bees were able to generalize among pollen types by evaluating the intensity of the pollen scent as well as the composition of the odorant mix, a trait that might provide information about pollen availability and abundance (Dobson et al., 1999). Honey bees generalize among aliphatic molecules with similar carbon chain lengths or carrying the same functional group (Guerrieri et al., 2005). However, natural floral scents (including pollen scents) are not pure substances, but complex mixtures of a great variety of molecules in different proportions. Consequently, honey bees must face the dilemma of generalizing among similar floral blends whose exact composition varies from one individual flower to another (Sandoz, 2011).

In the present study, we examined how honey bees generalize among scents from pollen grains of different plant species. Specifically, we asked if this generalization depended on plant species that are taxonomically related, nutritional characteristics of pollen (*e.g.* similar amounts of protein) or flowering period. To answer these questions, we performed *PER conditioning* and we evaluated generalization among the different pollen scents presented.

Material and methods

Determination of botanical origin, protein content and grain size of pollen types

Several pollen samples were collected from the honey bee hives at the field station of the National Institute of Agricultural Technology – Bariloche Research Lab (EEA INTA Bariloche, San Carlos de Bariloche, Province of Río Negro, Patagonia, Argentina, 41°7022.36″S, 71°1504.94″W). For pollen collection, we installed pollen traps (Apipolen®, Madrid, Spain) in three hives during 24 hours on three austral summer dates (23-November-2015; 29-December-2015 and 22-January-2016). Subsequently, nine samples (3 hives × 3

days) of mixtures of honey bee-collected pollen from different botanical origins were obtained. These samples were left to dry at room temperature (22°C) over 48 h. Afterwards, we selected sub-samples of 30 grams each and classified the different types of pollen loads according to their color, shape and texture, following the Filipiak's method for identification of *Pollen Pellet Morphospecies* (PPMs, Filipiak et al., 2017). Finally, we weighed and calculated the percentage of each PPM within the sub-samples and we selected the six most abundant PPMs (*i.e.* those with the highest percentages, values that vary between 30 and 50% of the subsample). The sub-samples per PPM type were divided into three lots: one to determine the botanical origin, a second for the analysis of protein content and the third to be used as conditioned stimulus during the experimental design.

To determine the botanical origin of the six types of PPM previously selected, we performed observations using (1) an optical microscope (OM) with samples mounted on slides (plus agar and safranin diluted at 90%) (Louveaux et al., 1978; Von Der Ohe et al., 2004); and (2) using a scanning electron microscope (SEM). The OM observations allowed a preliminary identification of the botanical origin of the PPM types at family level. Afterwards, we followed the SEM procedure developed by Pernal and Currie (2001), consisting of very high-resolution photographs of the pollen structures (Fig. S1). Photographs were captured at the Atomic Center of Bariloche (Centro Atómico Bariloche, Depto. Caracterización de Materiales - Servicio de Microscopia y Rayos X; San Carlos de Bariloche, Río Negro, Argentina). In these photographs, we observed and compared the morphological characteristics of the pollen with referenced material (Markgraf and D´Antoni, 1978; Valdés et al., 1987; González-Romano and Candau, 1989; Tellería and Forcone, 2002; Forcone et al., 2006). In addition, a post-identification validation was carried out via comparison between the plant species identified and their presence in the landscape surrounding the hives. Taxonomic identification of the pollen types allowed us to establish which types of pollen could be grouped to evaluate the effect of taxonomical family and flowering period.

In order to measure the protein content of each selected pollen we took a sub-sample of 0.15 g (weighed with a scale Acculab®) and performed a semi-micro Kjeldahl method with a block digester (Bremmer, 1996; Campos et al., 2008; Forcone et al., 2011). Protein content was estimated by multiplying the percentage amount of nitrogen by 6.25 (Van Soest, 1967). More details on the protein content of the selected pollen are available in Table S1 (Supporting information).

Honey bees

A total of 310 worker honey bees *Apis mellifera* were captured during March 2016. They were captured using transparent plastic containers placed at the entrances of 15 hives at the field station of the National Institute of Agricultural Technology – Bariloche Research Station. Between 10 and 30 individuals were captured per day from randomly selected hives, in order to carry out the experiments (see below). The collection was carried out in the early hours of the morning, as soon as the honey bees began their foraging activity. Once captured, honey bees were transported to the laboratory in plastic containers. Honey bees were anaesthetized by placing the container in a fridge at 4°C for five minutes and then kept on ice for no longer than 10 minutes. Subsequently, each individual was placed into an Eppendorf tube (5 ml), the tip of which had been cut off to enable the head of the honey bee be gently pushed through the hole. Each individual was then harnessed with tape on the back of the head allowing free movements of the antennae and mouthparts. After three hours honey bees' recovering from the anesthesia and prior to beginning the learning protocol, we tested the motivation of each individual to respond to sucrose by touching each honey bee's antennae with a toothpick imbibed in sucrose solution (50% w/v). This procedure was performed at 20.4 ± 2 °C and 39.6 ± 10 % RH. Those individuals that did not extend their proboscis when stimulated with sucrose solution were discarded (n = 42). To avoid any effect of external odors, the Eppendorf rack with the harnessed honey bees was placed inside an air extraction hood, between the extraction aperture of the air extraction and the syringe that released the olfactory stimuli (*i.e.* pollen scents). During the experiments, the airflow was maintained at minimum and the uniformity of the airflow of the extraction hood was controlled.

Conditioning

During the *Conditioning* phase, honey bees were trained to associate different pollen scents (Conditioned stimulus; CS) with a reward of sucrose solution (Unconditioned Stimulus; US). This procedure consisted in three conditioning trials (C1, C2, and C3); each trial lasted one minute and there was an inter-trial interval (ITI) of 10 minutes. Twenty-five seconds after the trial onset, we released the scent of a PPM (CS). The pollen scent was produced using 30 mg of a PPM type introduced via a 10-ml syringe, the piston was pulled back and air blown on to the antennae over five seconds. Three seconds later, sucrose solution was presented to the honey bee by touching both the antennae and proboscis with the imbibed toothpick (US). US presentation lasted five seconds (Fig. S2). As a control, a similar protocol to the conditioning treatment was performed but no pollen was put inside the syringe (in this case we expected no PER). We randomly assigned individuals to the different treatments (Six treatments: one treatment per PPM). Those individuals that performed a PER in to the US at the first conditioning trial or those that did not respond to the CS in any trial were discarded for subsequent data analysis (n = 55).

Among the total number of individuals used (n = 310), 55 honey bees were discarded for the entire data analysis procedure because they did not show PER during all of the conditioning trials or did not respond immediately to sugar water (n = 42) or responded positively to pollen in the first trial before the unconditioned stimuli (n = 13). We performed this selection, considering three aspects: (1) the absence of PER performance by individuals in any of the conditioning trials could be related to an inadequate recovery of the anesthesia. (2) The absence of response to sucrose solution as a reward could be related to the honey bees being assayed as nectar foragers. Reade and Naug (2016), demonstrated that foraging decisions in honey bees were determined by individual requirements of carbohydrates and that pollen foragers have higher carbohydrate intake than nectar foragers. (3) PER to pollen scent in the first trial could indicate a previous association between pollen scent and sucrose. In those cases, we would not induce any learning during our experiments. Therefore, those individuals that extended their probosces when presented with pollen scent in the first *conditioning* trial were excluded from the data analyses, those cases were distributed among pollen types 3, 4, 5 and 6 (n = 13; Fig. S3). Additionally, 18 honey bees were used for control treatment and

all responded positively only to the US. Thus, the remaining honey bees (*n*=237; 76%) were used for the experiments.

Test

The *Test* phase began ten minutes (ITI) after performing the *Conditioning* phase. During the *Test*, honey bees were presented with four different pollen scents, in a sequence of four trials with ITI of ten minutes. No reward was presented during the *Test*. The goal of this phase was to evaluate whether honey bees would respond to conditioned and to novel stimuli (*i.e.* a type of pollen different from the one used for *Conditioning*). Honey bees would extend their probosces when presented with novel stimuli if those stimuli were perceived as similar to the CS, thus providing evidence of generalization. To avoid any bias due to the sequence in which scents were to be presented, the order of test stimuli was established following a randomized sequence. For example: we used Pollen 1 for *Conditioning* and Pollen 3, Pollen 5, Pollen 1 and Pollen 4 for *Test*. Given the randomness of the sequence, in some situations, it happened that within the pollen types used at the *Test* phase was present or not the same pollen used for *Conditioning.* Therefore, the combinations have different sample size (for details see Guerrieri et al., 2005). By performing a random sequence of four trials to test the six types of pollen, the duration of the protocol and the fatigue of the experimental individual were reduced, preventing the honey bee from diminishing its response capability.

Data analyses

All statistical analyses were performed using the R Project for Statistical Computing version 3.5.1 (R Development Core Team, 2018).

Conditioning –The correlative link between the proportion of successful PER at C2 and C3 was tested by a Pearson correlative test. By means of an ANOVA within the GLM framework, we analyzed whether there were differences between the success of PER for each PPM type at trial 3. Following the same analytic approach, we also evaluated whether different characteristics of pollen part-explained variation in the level of PER at C3. We analyzed the effect of two pollen traits as size of pollen grain and protein amount and (based on the characterization of botanical origin) we also considered taxonomic classification and

flowering period. Differences in the levels of PER at C2 (fixed effect) and C3 (response variable) was tested by binomial General Linear Model (GLM) with a logit link function. Model residuals were extracted and inspected against fitted values (residuals *vs.* fitted plot and normal Q-Q plot) to ensure residual normality and homoscedasticity assumptions were fulfilled.

Test – The correlative link between the proportion of successful PER at C3 (fixed effect) and Test (response variable) was evaluated as a learning validation test, using binomial GLM with a logit link function. Model residuals were also extracted and inspected against fitted values. In a similar way to data analysis carried out for *Conditioning*, four ANOVAs were performed to evaluate the possible effect of pollen traits (size of pollen grains and amount of protein), taxonomical family and temporary distance of flowering (*i.e.* lapse of time between end of flowering and the execution of the experiment on March) on the level of PER. It should be noted that for this analysis we only used the results obtained when a given individual was conditioned and tested with the same type of pollen.

Generalization -In order to determine the perceptual similarity among different pollen scents, we successively renamed each pollen identity by the name of others following a matrix of simplification (see Table S5). For instance, the pollens P1, P2 and P3 were first named “A, B, C” as its original identity and then simplified for similarity test with the renames of “A, B, B”, “A, A, B”, “A, B, A” and “A, A, A” (the similarity between the three pollens is tested with the latter scenario). Thus, the six pollen identities were renamed along all the possible 56 simplified combinations of renamed identity scenarios. Binomial GLMs were then used to compare the proportion of successful PER (response variable) to the renamed pollen identity (fixed factor) (Table S6). Following a heuristic approach, all the possible combinations of scenarios were evaluated. The candidate models were ranked according to the Akaike information criterion (AIC) to find the best compromise between fit and complexity (*i.e.* models with Δ AIC < 10). From the selected model, differences between each pollen type were evaluated with a posteriori multiple pairwise comparison (Tukey HSD test).

Results

Determination of botanical origin, protein content and grain size of pollen types

From the six pollen selected, the following botanic origins were determined: Pollen 1: *Pyracantha coccinea* Roemer (Rosales: Rosaceae); Pollen 2: *Capsella bursa-pastoris* Linnaeus (Brassicales: Brassicaceae); Pollen 3: *Carduus thoermeri* Linnaeus (Asterales: Asteraceae); Pollen 4: *Hypochaeris radicata* Linnaeus (Asterales: Asteraceae); Pollen 5: *Diplotaxis tenuifolia* Linnaeus (Capparales: Brassicaceae); Pollen 6: *Salix humboldtiana* Willdenow (Malpighiales: Salicaceae). The Figure S1 shows the morphology of each selected pollen. Most of these plant species are exotic in Patagonia, Argentina (Table S1), where the experiments were performed. Since we were only interested in identifying the pollen grains of the dominantly harvested plants, we did not deepen in the taxonomically identification of the rest of the pollen loads.

Among the pollen grains identified, the percentage of protein content varied from 16.87 % in Pollen 3 (*C. thoermeri*) to 24.37 % in Pollen 2 (*C. bursa-pastoris*) (Table S1). Regarding to the size of pollen grain, Pollen 3 has the largest size (Polar axis = 43-52 µm; Equatorial diameter = 49-55µm) while Pollen 6 (*S. humboldtiana*) is the smallest (Polar axis = 18-22µm; Equatorial diameter = 15-19µm). To evaluate the effect of taxonomical family were established four category: Rosaceae (Pollen 1), Brassicaceae (Pollen 2 and 5), Asteraceae (Pollen 3 and 4) and Salicaceae (Pollen 6). We also established two categories of flowering period according to the end the blooming period: Spring and early Summer (Pollen 1, 2 and 6; which end their flowering in Nov-Dec); Summer and early Autumn (Pollen 3, 4 and 5; which end their flowering in Feb-March). More details on flowering and pollen traits are available in Table S1.

Conditioning

The level of PER increased during the conditioning trials for each pollen type (Fig.1A). The proportion of PER value varied from 0.52 to 0.90 at C2 and from 0.72 to one at C3. PER level was highest when honey bees were trained with Pollen 1, followed by Pollen 6 and Pollen 2. The level of PER in the third conditioning trial (C3) was positively correlated with the PER level in the second conditioning trial (C2) (Pearson's Rank Correlation coefficient $r_P = 0.938$, $P = 0.006$, t = 5.409, df = 4; Fig. 1B). This suggested that honey bees

would be able to associate the scent of pollen in the second trial and there is no loss of learning (due to fatigue) in the next trial. The last conditioning trial (C3) showed high PER levels for each pollen type (*i.e.* 0.72–1), without significant species effect on the learning success (binomial GLM, $Z = 1.905$, $P = 0.342$, Table S2, Fig. 1C). The ANOVAs performed between the particular traits of each type of pollen and PER at C3, showed no significant differences unlike to the effect of grouped pollen according to end of flowering ($F = 10.86$. $P = 0.030$, df = 1, Table 1, Fig. 1D). Those types of pollen which end their flowering period early in the season (Pollen 1, 2 and 6) exhibits a higher level of PER.

Test

Honey bees showed a lower level of PER during the *Test* phase as compared to the *Conditioning* phase, varying from 0.52 (Pollen 6) to 0.66 (Pollen 1). Similarly to the *Conditioning* phase, no effect of pollen type was detected on the level of PER at *Test* (GLM, P = 0.264, Table S3, Fig. 2A). The level of PER at *Test* was not correlated with the level of PER at C3 of the *Conditioning* phase ($r_P = 0.195$, t = 0.398, df = 4, $P = 0.711$, Fig. 2B). There was a decrease in the PER level in the *Test* phase and we assume that this is perhaps a consequence of the honey bee's fatigue due to the duration of the experimental protocol. The variability in the level of PER among the presented pollen types was not significantly explained by the pollen traits ($P_{\text{Grain size}}=0.723$, $P_{\text{Taxonomical family}}=0.275$, $P_{\text{Protein amount}}= 0.260$) or pollen grouped by flowering period ($P = 0.734$, see statistics in Table 2).

Generalization

The generalization matrix (which related the level of PER between both phases of the learning protocol for each combination of pollen types. Fig. 3A, Table S4) showed that higher levels of PER corresponded to those trials in which was used the same pollen type in both phases (main diagonal). The matrix structure was asymmetric, showing that honey bees did not respond in the same way when a pair of pollen types from *Conditioning* to *Test* were interchanged. For example, when pollen 1 was used for *Conditioning* and pollen 3 for *Test*, we observed a proportion of 0.57 of PER but for the inverse combination (Pollen 3 for *Conditioning* and Pollen 1 for *Test*) the level of PER decrease to 0.5.

According to the mean values of PER at the generalization matrix there was a pair of pollen combination that showed higher levels of PER suggesting that both pollen types were perceive as similar: P2-P1 (0.73), P1-P3 (0.57) and P4-P1 (0.67). However, since two or more types of pollen could be perceived as similar, 56 models (Binomial GLMs) were performed to analyze different combinations (Table S5). Five models were thus selected (Table S5). These models included the same four types of pollen (P1, P2, P3, P4), that exert the higher levels of PER at the generalization matrix. First model selected (Δ AIC = 0, Z = 5.273; $P < 0.01$) established that honey bees perceived Pollen 1 and Pollen 4 as equals, while the second model suggested that also Pollen 2 is similar to Pollen 1 and Pollen 4 (Δ AIC = 5.723, Z = 4.719; $P < 0.01$).

These results were in agreement with those obtained by the simple models (in which it is established that one type of pollen differs from the rest), since there were not significant differences for Pollen 2 (Model N° 50; Δ AIC = 27.587, Z = -0.867, P = 0.386) and Pollen 4 (Model N° 43; Δ AIC =26.221, Z = 1.463, P = 0.144). Whilst, Pollen 1, Pollen 3, Pollen 5 and Pollen 6 were perceived as different from the rest (P1 (Model N° 27; Δ AIC = 21.074, Z = -2.707, $P < 0.01$), P3 (Model N° 39; Δ AIC = 24.469, Z = 1.964, $P < 0.05$), P5 (Model N° 24; Δ AIC = 19.464, Z = 2.938, $P < 0.01$), P6 (Model N° 33; Δ AIC = 23.028, Z = 2.289, $P < 0.05$) (Fig. 3B)).

The *a posteriori* analysis of the level of PER for each pollen type assuming P1=P4 (selected model) shows non-significant differences (Fig. 4A, Table S6). These results were confirmed by the estimates of Akaike weights value (Fig. 4B).

Discussion

We studied honey bees' ability to generalize among pollen scents from different plant species. The majority of the pollen types identified belonged to exotic plant species in Patagonia, southern Argentina, and had different nutritional and phenological characteristics (Forcone et al., 2005; Tellería and Forcone, 2000).

During the *Conditioning* phase of the experiment, some stimuli induced greater levels of PER than others, *e.g*. Pollen 1 (*Pyracantha coccinea*), Pollen 2 (*Capsella bursa-pastoris*) and Pollen 6 (*Salix humboldtiana*). Overall, the level of PER was independent of the amount of protein, grain size or taxonomical family. This observation is consistent with previous studies that showed similar results and demonstrated that these variables are unlikely to serve for recognition cues (Schmidt and Johnson, 1984; Schmidt et al., 1987). However, when we grouped pollen types according to the end of the flowering period, we found that pollen from flowers of early ending produce higher levels of PER (e.g. Pollen 6, *S. humboldtiana*). Arenas and Farina (2014) demonstrated that early experiences might have a fundamental role for the preferences towards certain types of pollen by honey bees of older ages (17 days of age). They argued that within the hive, young honey bees perceive and even may learn many odors whilst performing tasks such as nursing or food processing which enables the formation of a pollen preferences in foragers (Arenas and Farina, 2014; Cholé et al., 2019). Moreover, several studies showed that the honey bees become imprinted to pollen odor during pre-imaginal stages and subsequently as adults show a preference for the same scent (Dobson, 1994; Masson and Arnold, 1984). Based on these reports, we assume that, in our experiments, honey bees performed higher level of PER toward pollen of flowers available in early Summer (November–December) and that those scents may remind the honey bees the odors perceived in the hive during their first days as adults, before becoming foragers. In fact, we used forager individuals (over 21 days) and when we performed the experiment the early seasonal flowers were not available in the environment. In future work it would be interesting to study learning in adult honey bees of different ages and their ability to memorize olfactory stimuli such as pollen scents.

At *Test* phase, despite there were no significant differences in the level of PER among the different pollen scents, Pollen 1 (*P. coccinea*) continued to induce the highest level of PER. Not phylogenetic relatedness, protein content of the pollen or grouped pollen had any influence on the level of PER. Similar results were obtained in other studies in which it had been determined that size and protein content of pollen were unlikely to serve as recognition cues in honey bees during foraging behavior (Levin and Bohart, 1955; Schmidt and Johnson,1984; Schmidt *et al*., 1987; Pernal and Currie, 2002). Possibly, other chemical compounds regardless of the nutritional value of the pollen source (as phago-stimulants or

phago-deterrents, secondary metabolites, the presence of pollenkit or volatile compounds) as well prior experience may influence honey bee preferences (Cook et al. 2003; Nicholls and Hempel de Ibarra, 2017). Numerous studies have provided evidence for a chemical source for pollen recognition cues (Doull, 1966; Lepage and Boch, 1968; Robinson and Nation, 1968; Doull and Standifer, 1969; Schmidt, 1985; Hanna and Schmidt, 2004; Pacini and Hesse, 2005), but none of them have successfully identified any compounds in pollen that serve this role.

When we analyzed (with the generalization matrix) which pollen scents honey bees perceived as similar, we observed that those individuals conditioned to Pollen 4 (*H. radicata*) generalized to Pollen 1 (*P. coccinea*). However, honey bees conditioned to Pollen 1 did not generalize towards pollen 4 with the same level of PER, but they do so in a smaller proportion. Therefore, generalization was asymmetric, indicating that the level of PER between any pair of stimuli depended on the order in which the stimuli were presented. Generalization asymmetry is a common phenomenon and has been reported in previous articles (Guerrieri et al., 2005; Schubert et al., 2015; see also an analogous case in ants reported by Bos et al., 2013), suggesting that our observation is an ordinary outcome. Chemical characteristics of pollen that we evaluated did neither explain the differences among the levels of PER at *Conditioning* and *Test*, nor why certain pairs of pollen were generalized. The main feature to be noticed is the fact that both species were founded simultaneously during early Summer (November-December).

Ghirlanda and Enquist (2003) proposed that all the animals are able to generalize if the stimuli have similar ecological value. Moreover Guerrieri et al. (2005) demonstrated that the chemical group and chain length of odor molecules determined the honey bees' generalization responses. This led us to hypothesize that the pair of pollen types generalized by honey bees possibly possess similar chemical composition of volatile compounds, which emit olfactory cues with the predominance of certain molecules that promote generalization (*e.g* Aldehydes like hexanal). According to Wright and Schiestl (2009), unrelated plant species may have similar floral scents with common volatile compounds due to selection pressure of a specific pollinator.

Guerrieri et al. (2005) also demonstrated that honey bees conditioned to aldehydes generalized very little to odors belonging to other functional groups and contrarily, honey bees conditioned to other functional groups highly generalized to aldehydes. This showed that generalization between aldehydes and molecules containing other functional groups was asymmetrical, analogous results could be visualized in our generalization matrix. Therefore, we suggest that a high level of PER in the *Test* when honey bees were presented with a novel pollen was due to the novel pollen scent containing a great proportion of aldehydes.

Pollen scents are species-specific and honey bees may recognize pollen inter-specific differences and infer the quality based on the content of only some amino acids using this information for their foraging decisions (Dobson and Bergström, 2000; Cook et al., 2003; Piskorski et al., 2011; Ruedenauer et al., 2019). It remains unclear, which perceptual cues determined honey bees generalizing among plants present in Patagonia. In any case, it will be interesting to analyze, the adaptive implications of the generalization from one type of pollen with low protein content (e.g. Pollen 4) to another with medium protein content (e.g. Pollen 1). This behavior possibly benefits the hive development, in fact, the ability to generalize plays a key role in reducing the cost of foraging, where different flowers can give similar rewards in the form of nectar and pollen (Waser et al., 1996). However, we also demonstrated that generalization could occur inversely - from pollen with high protein content (e.g. Pollen 2, *C. bursa-pastoris*) to another with medium protein (Pollen 1, *P. coccinea*).

Wright et al. (2008) argued that olfactory generalization is a mechanism used by animals to adjust their sensitivity to differences in complex olfactory stimuli in a context-dependent manner. Consequently, this ability plays a key role in reducing the cost of foraging, since it allows honey bees to successfully forage in a changing environment decreasing distances, duration and number of flights (Waser et al. 1996). Therefore, identifying the types of pollen that were perceived as similar (but have different nutritional qualities and/or flowering period) can provide valuable information for beekeepers and agricultural producers, since it allows them to carry out a management of the floral offer (selecting flowers of high nutritional resource) to obtain a greater production of honey or a better pollination service. In-depth studying of honey bee selection behavior will enhance the sustainable management of beehives. Our results contribute to the background of knowledge

about the complex cognitive performances of honey bees and are in agreement with previous researches, which evidenced how pollen scent could be a crucial cue of honey bee foraging behavior (Wright and Smith 2003; Cook et al., 2005; Arenas and Farina 2012; Balamurali et al., 2015. The ability of pollen odor generalization could exert an important selective pressure determining plant reproductive success and plant co-evolution, however, our knowledge about how olfactory learning in pollinators determine the expression of these floral cues remains relatively poor (Wright and Schiestl, 2009). As we observed, perceptual similarity among pollen scents not only relies on chemical cues, but also on the temporality of the flowering season. Therefore, temporality role as a dimension in perceptual spaces deserves being taken into account in future cognitive studies.

We also considered that would be of great interest to conducting studies with an integrated approach (between behavioral ecology and neuroscience) to understand the mechanisms by which pollen scents are processed in the honey bee neural system. This information could improve our understanding about the pollinator-plant interaction as well about the processes that underlie floral signals evolution (Balamurali et al., 2015; Rush et al., 2016).

Acknowledgements

Special thanks are given to Dr. Octavio Bruzzone (IFAB, INTA EEA Bariloche) for his constructive comments on an earlier version of this manuscript and for establishing the international collaboration between INTA-Bariloche (Argentina) and IRBI (University of Tours, France). In addition, we want to thank the support and collaboration that the Dr. Claudio Lazzari gave us during the development of this project. Thanks to Paula Ariadna Troyón for helping us performing SEM photographs at Bariloche Atomic Center (Centro Atómico Bariloche, Depto. Caracterización de Materiales - Servicio de Microscopia y Rayos X. San Carlos de Bariloche, Río Negro, Argentina). We also thank Laura Borrelli (INTA-Bariloche) for her help with microscopy techniques and to Joshua Taylor for improving the writing of the manuscript in English. The authors would also like to acknowledge Argentine Government's policies for education, science, and technology carried out between 2003 and 2015, which supported the development of this research.

Competing interests

All authors declare that there are no conflicts of interest.

Funding

This work was financially supported by Marie Sklodowska Curie actions – FP7-IRSES (grant No. 319015: IBIAL – Integrative biology of Insects Affecting human Life) from the EU, and by PATNOR 1281102-INTA Argentina.

FG was assigned a "Dr. César Milstein" grant in 2015 (Programa RAICES, Ministerio de Ciencia, Tecnología e Innovatión Productiva, Presidencia de la Nación Argentina).

ALP and FR were post-doctoral fellows of CONICET (National Research Council, Argentina). ALP is presently a permanent researcher of CONICET at EEA INTA Bariloche.

Authors' contributions

ALP, VFA and FG conceived and designed the experiments; ALP performed the experiments and performed the analysis of pollen samples; FR analyzed the data; JW collaborated in the identification and characterization of pollen samples; and GH made the breeding and handling of honey bees, and collected pollen samples; ALP, FR, VFA and FG wrote the paper; all authors gave their final approval for publication.

References

Arenas, A. and Farina, W. M. (2012). Learned olfactory cues affect pollen-foraging preferences in honeybees, *Apis mellifera*. *Anim. Behav*. **83**, 1023-1033.

Arenas, A. and Farina, W. M. (2014). Bias to pollen odors is affected by early exposure and foraging experience. *J. Insect Physiol.* **66**, 28- 36.

Avarguès-Weber, A., Deisig, N. and Giurfa, M. (2011). Visual Cognition in Social Insects. *Annu. Rev. Entomol.* **56**, 423-443.

Balamurali, G. S., Krishna, S. and Somanathan, H. (2015). Senses and signals: evolution of floral signals, pollinator sensory systems and the structure of plant–pollinator interactions. *Curr. Sci.* **108** (10), 1852- 1861.

Baracchi, D., Rigosi, E., de Brito Sanchez, G. and Giurfa, M. (2018). Lateralization of sucrose responsiveness and non-associative learning in honey bees front. *Psychol.* **9** (425). DOI: 10.3389/fpsyg.2018.00425

Beekman, M., Preece, K. and Schaerf, T. (2016). Dancing for their supper: do honeybees adjust their recruitment dance in response to the protein content of pollen? *Insectes Soc*. **63**, 117-126.

Benard, J., Stach, S. and Giurfa, M. (2006). Categorization of visual stimuli in the honeybee *Apis mellifera*. *Anim. Cogn.* **9** (4), 257-270.

Bitterman, M. E., Menzel, R., Fietz, A. and Schafer, S. (1983). Classical conditioning of proboscis extension in honeybees (*Apis mellifera*). *J. Comp. Psycho1*. **97**, 107-l19.

Bos, N., Roussel, E., Giurfa, M. and d´Ettorre, P. (2013). Appetitive and aversive olfactory learning induce similar generalization rates in the honey bee. *Anim. Cogn.* **17** (2) DOI: 10.1007/s10071-013-0671-6

Bremner, J. M. (1996). Nitrogen-Total (Chapter 37, pp.1085-1121). In: Bigham, J. M (ed.) Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series Nr. 5.

Campos, M. G. R., Bogdanov, S., Bicudo de Almeida-Muradian, L., Szczesna, T., Mancebo, Y., Frigerio, G. and Ferreira, F. (2008). Pollen composition and standardization of analytical methods. *J. Api. Res*. **47**(2), 154-161.

Chittka, L., Thomson, J. D. and Waser, N. M. (1999). Flower Constancy, Insect Psychology, and Plant Evolution. *Naturwissenschaften*, **86** (8), 361-377.

Cholé, H., Carcaud, J., Mazeau, H., Famié, S., Arnold, G. and Sandoz, J. C. (2019) Social contact acts as appetitive reinforcement and supports associative learning in honeybees. *Curr. Biol.* **29** (8), 1407-1413.e3

Cook, S. M., Awmack, C. S., Murray, D. A. and Williams, I. H. (2003). Are honey bees' foraging preferences affected by pollen amino acid composition? *Ecol. Entomol.* **28**, 622-627.

Cook, S. M., Sandoz, J. C., Martin, A. P., Murray, D. A., Poppy, G. M. and Williams, I. H. (2005). Could learning of pollen odours by honey bees (*Apis mellifera*) play a role in their foraging behavior? *Physiol. Entomol.* **30**, 164-174.

Deisig, N., Lachnit, H. and Giurfa, M. (2002). The effect of similarity between elemental stimuli and compounds in olfactory patterning discriminations. *Learn. Mem.* **9**, 112-121.

Deisig, N., Lachnit, H., Sandoz, J. C., Lober, K. and Giurfa, M. (2003). A modified version of the unique cue theory accounts for olfactory compound processing in honeybees. *Learn. Mem.* **10**, 199-208.

Di Pasquale, G., Salignon, M., Le Conte, Y., Belzunces, L. P., Decourtye, A., Kretzschmar, A., Suchail, S., Brunet, J. L. and Alaux, C. (2013). Influence of pollen nutrition on honey bee health: do pollen quality and diversity matter? *Plos One* **8**: e72016. DOI:10.1371/journal.pone.0072016

Dobson, H. E. (1994). Floral volatiles in insect biology. In: Insect-Plant Interactions, (ed. E. A. Bernays) Boca Raton: CRC Press), pp. 47-81.

Dobson, H. E. and Bergstrom, G. (2000). The ecology and evolution of pollen odors. *Plant Syst. Evol.* **222**, 63-87.

Dobson, H. E., Danielson, E. M. and Wesep, I. D. V. (1999). Pollen odor chemicals as modulators of bumble bee foraging on *Rosa rugosa* Thunb.(Rosaceae). *Plant Spec. Biol.* **14**, 153-166.

Doull, K. M. (1966) The relative attractiveness to pollen-collecting honey bees of some different pollens. *J. Apic. Res.* **5**, 9-14.

Doull, K. M. and Standifer, L. N. (1969). A technique for measuring feeding responses of honeybees in their hive. *J. Apic. Res.* **8** (3), 153-157.

Fewell, J. H. and Winston, M. L. (1992). Colony state and regulation of pollen foraging in the honey bee, *Apis mellifera* L. *Behav. Ecol. Sociobiol.* **30**, 387-393.

Filipiak, M., Kuszewska, K., Asselman, M., Denisow, B., Stawiarz, E., Woyciechowski, M. and Weiner, J. (2017). Ecological stoichiometry of the honeybee: Pollen diversity and adequate species composition are needed to mitigate limitations imposed on the growth and development of bees by pollen quality. *PLoS ONE* **12**(8), e0183236. https://doi.org/10.1371/journal.pone.0183236

Forcone, A., Aloisi, P. V., Ruppel, S. and Muñoz, M. (2011). Botanical composition and protein content of pollen collected by *Apis mellifera* L. in the north-west of Santa Cruz (Argentinean Patagonia), *Grana* **50** (1), 30-39.

Forcone, A., Ayestarán, G., Kutschker, A. and García, J. (2005). Palynological characterization of honeys from the Andean Patagonia (Chubut, Argentina). *Grana* **44** (3), 202-208.

Forcone, A., García, J. and Ayestarán, G. (2006). Polen de las mieles de la Patagonia Andina (Chubut- Argentina). *Bol. Soc. Argent. Bot.* **41** (1-2), 25-39.

Free, J. B. (1963). The flower constancy of honeybees. *J. Anim. Ecol.* **32** (1), 119-131.

Gerber, B., Geberzahn, N., Hellstern, F., Klein, J., Kowalksi, O., Wüstenberg, D. and Menzel, R. (1996). Honey bees transfer olfactory memories established during flower visits to a proboscis extension paradigm in the laboratory *Anim. Behav.* **52,** 1079-1085.

Getz, W. M. and Smith, K. B. (1987). Olfactory sensitivity and discrimination of mixtures in the honeybee *Apis mellifera*. *J. Comp. Physiol. A* **160**, 239-245.

Ghirlanda, G. and Enquist, M. (2003). A century of generalization. *Anim. Behav.* **66** (1), 15-36.

Giles, A. C. and Rankin, A. H. (2009). Behavioral and genetic characterization of habituation using *Caenorhabditis elegans*. *Neurobiol. Learn. Mem.* **92**,139-146.

Giurfa, M, and Sandoz, J. C. (2015). Invertebrate learning and memory: Fifty years of olfactory conditioning of the proboscis extension response in honeybees. *Learn. Mem.* **19**, 54-66.

Giurfa, M. (2003). Cognitive neuroethology: dissecting non-elemental learning in a honeybee brain. *Curr. Opin. Neurobiol*. **13**, 726-735.

Giurfa, M. (2007). Behavioral and neural analysis of associative learning in the honeybee: a taste from the magic well. *J. Comp. Physiol. A* **193**, 801-824.

Giurfa, M. (2015). Learning and cognition in insects. *Wires Cognitive Science* **6** (4), 383-395.

Giurfa, M., Eichmann, E. and Menzel, R. (1996). Symmetry perception in an insect. *Nature* **382**, 458-461.

González-Romano, M. L. and Candau, P. (1989). Contribución de la palinología de Rosaceae. *Acta Bot. Malac.* **14**, 105-116.

Guerrieri, F., Schubert, M., Sandoz, J. C., Giurfa, M. (2005). Perceptual and neural olfactory similarity in honeybees. *PLoS Biol* **3**(4), e60.

Gumbert, A. (2000). Color choices by bumble bees (*Bombus terrestris*): innate preferences and generalization after learning. *Behav. Ecol. Sociobiol*. **48**, 36-43.

Hammer, M. and Menzel, R. (1995). Learning and memory in the honeybee. *J. Neurosci*. **15**, 1617-1630.

Hanna, A. and Schmidt, J. (2004). Effect of phagostimulants in artificial diets on honey bee feeding behavior. *Southwest. Entomol.* **29** (4), 253-261.

Horridge, A. (2009). Generalization in visual recognition by the honeybee (*Apis mellifera*) A review and explanation. *J. Insect Physiol* **55**, 499-511.

Laska, M., Galizia, G., Giurfa, M. and Menzel, R. (1999). Olfactory discrimination ability and odor structure–activity relationships in honeybees. *Chem. Senses* **24**, 429-443.

Lepage, M. and Boch, R. (1968). Pollen lipids attractive to honeybees. *Lipids* **3** (6), 530-534.

Levin, M. D., and Bohart, G. E. (1955). Selection of Pollens by Honey Bees. Amer. *Bee Jour.* **95** (10), 392-393

Louveaux, J., Maurizio, A. and Vorwohl, G. (1978). Methods of Melissopalynology International Commission for Bee Botany of IUBS. *Bee World* **59** (4), 139-157.

Markgraf, V. and D´Antoni, H. L. (1978). Pollen flora of Argentina: modern spore and pollen types of Pteridophyta, Gymnospermae, and Angiospermae. University of Arizona Press, Tucson, 208pp.

Masson, C. and Arnoldm G. (1984). Ontogeny, maturation and plasticity of the olfactory system in the workerbee. *J. Insect Physiol.* **30** (1), 7-14.

Matsumoto, Y., Menzel, R., Sandoz, J.C. and Giurfa, M. (2012). Revisiting olfactory classical conditioning of the proboscis extension response in honey bees: A step toward standardized procedures. *J. Neurosci. Methods* **211**, 159-167.

Menzel, R. (1985). Learning in honey bees in an ecological and behavioral context. In: Experimental and Behavioral Ecology (ed. B. Hölldobler and M. Lindauer), pp. 55-74. Stuttgart: Fischer.

Menzel, R. (1999). Memory dynamics in the honeybee. *J. Comp. Physiol. A* **185**, 323-340.

Menzel, R. (2001). Searching for the memory trace in a mini-brain, the honeybee. *Learn. Mem*. **8**, 53-62.

Menzel, R. and Erber, J. (1978). Learning and memory in honeybees. *Sci. Am.* **239**, 102-111.

Muth, F., Papaj, D. R. and Leonard, A. S. (2016). Bees remember flowers for more than one reason: pollen mediates associative learning. *Anim. Behav.* **111**, 93-100.

Nicholls, E. and Hempel de Ibarra, N. (2017). Assessment of pollen rewards by foraging bees. *Funct. Ecol.* **31**, 76-87.

Nicolson, S. W. (2011). Bee food: the chemistry and nutritional value of nectar, pollen and mixtures of the two. *Afr. Zool.* **46** (2), 197-204.

Pacini, E. and Hesse, M. (2005). Pollenkitt – its composition, forms and functions. *Flora* **200** (5), 399-415.

Pernal, S. F. and Currie, R. W. (2001). The influence of pollen quality on foraging behavior in honeybees (*Apis mellifera* L.). *Behav. Ecol. Sociobiol*. **51**(1), 53-68.

Pernal, S. F. and Currie, R. W. (2002). Discrimination and preferences for pollen-based cues by foraging honeybees, *Apis mellifera* L. *Anim. Behav*. **63**, 369-390.

Piskorski, R., Kroder, S. and Dorn, S. (2011). Can pollen headspace volatiles and pollenkitt lipids serve as reliable chemical cues for bee pollinators? *Chem. Biodivers.* **8**, 577-586.

R Development Core Team. (2018) R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Reade, A. J. and Naug, D. (2016) Inter-individual variation in nutrient balancing in the honeybee (*Apis mellifera*). *J. Insect Physiol.* **95**, 17-22.

Reinhard, J., Sinclair, M., Srinivasan M. V. and Claudianos, C. (2010). Honeybees learn odour mixtures via a selection of key odorants. *PLoS ONE* **5**(2), e9110. https://doi.org/10.1371/journal.pone.0009110.

Requier, F., Odoux, J. F., Henry, M. and Bretagnolle, V. (2017). The carry-over effects of pollen shortage decrease the survival of honey bee colonies in farmlands. *J. Appl. Ecol.* **54** (4), 1161–1170. DOI:10.1111/1365-2664.12836

Requier, F., Odoux, J. F., Tamic, T., Moreau, N., Henry, M., Decourtye, A. and Bretagnolle, V. (2015). Honey-bee diet in intensive farmland habitats reveals an unexpectedly high flower richness and a critical role of weeds. *Ecol. Appl.* **25**, 881-890.

Robazzi Bignelli Valente Aguiar, J. M., Roselino, A.C., Sazima, M. and Giurfa, M. (2018). Can honey bees discriminate between floral-fragrance isomers? *J. Exp. Biol.* DOI: 10.1242/jeb.180844.

Robinson F. A. and Nation, J. L. (1968). Substances that attract caged honeybee colonies to consume pollen supplements and substitutes. *J. Apic. Res.* **7** (2), 83-88.

Roulston, T. H. and Cane, J. H. (2000). Pollen nutritional content and digestibility for animals. *Plant Syst. Evol*. **222**, 187-209.

Ruedenauer, F. A., Leonhardt, S. D., Lunau, K. and Spaethe, J. (2019). Bumblebees are able to perceive amino acids via chemotactile antennal stimulation. *J Comp Physiol A* https://doi.org/10.1007/s00359-019-01321-9

Ruedenauer, F. A., Spaethe, J. and Leonhardt, S. D. (2015). How to know which food is good for you: bumblebees use taste to discriminate between different concentrations of food differing in nutrient content. *J. Exp. Biol*. **218**, 2233-2240.

Ruedenauer, F. A., Wöhrle, C., Spaethe, J. and Leonhardt, S. D. (2018). Do honeybees (*Apis mellifera*) differentiate between different pollen types? *PLoS ONE* **13** (11): e0205821. DOI:10.1371/journal.pone.0205821

Rush, C., Broadhead, G. T., Raguso, R. A. and Riffell, J. A. (2016). Olfaction in context - sources of nuance in plant–pollinator communication. *Curr. Opin. Insect Sci.* **15**, 53-60.

Sandoz, J. C. (2011). Behavioral and neurophysiological study of olfactory perception and learning in honeybees. *Front. Syst. Neurosci.* **5** (98), doi: 10.3389/fnsys.2011.00098

Scheiner, R., Page, R. and Erber, J. (2004). Sucrose responsiveness and behavioral plasticity in honey bees (*Apis mellifera*). *Apidologie* **35** (2), 133-142.

Schmidt, J. O. and Johnson, B. E. (1984). Pollen feeding preference of *Apis mellifera*, a polylectic bee. *Southwest. Entomol.* **9**, 41-47.

Schmidt, J. O., Thoenes, S. C. and Levis, M. D. (1987). Survival of Honey Bees, *Apis mellifera* (Hymenoptera: Apidae), Fed Various Pollen Sources. *Ann. Entomol. Soc. Am.* **80** (2), 176-183.

Schmidt, J. O. (1985) Phagostimulants in pollen. *J. Apic. Res*. **24**, 107-114.

Schubert, M., Sandox, J. C., Galizia, G. and Giurfa, M. (2015). Odourant dominance in olfactory mixture processing: what makes a strong odourant? *Proc. R. Soc. B* **282**, 20142562. http://dx.doi.org/10.1098/rspb.2014.2562

Smith, B. and Menzel, R. (1989). The use of electromyogram recordings to quantify odorant discrimination in the honey bee, *Apis mellifera*. *J Insect Physiol* **5**, 369-375.

Stach, S., Benard, L. and Giurfa, M. (2004). Local-feature assembling in visual pattern recognition and generalization in honeybees. *Nature* **429**, 758–761.

Takeda, K. (1961). Classical conditioned response in the honey bee. *J. Insect Physiol.* **6** (3), 168-179.

Tedjakumala, R.S. and Giurfa, M. (2013). Rules and mechanisms of punishment learning in honey bees: the aversive conditioning of the sting extension response. *J. Exp. Biol.* **216**, 2985-2997.

Tellería, M. C. and Forcone, A. (2000). El polen de las mieles del valle de Río Negro, provincia Fitogeográfica del monte (Argentina). *Darwiniana* **38** (3-4), 273-277.

Tellería, M. C. and Forcone, A. (2002). Morfología del polen de las mieles del valle de Río Negro, valle inferior del río Chubut y llanura del río Senguer (Patagonia Argentina). *Bol. Soc. Argent. Bot*. **37**, 235-250.

Valdés, B., Díez, M. J. and Fernández, I. (1987). Atlas polínico de Andalucía Occidental. Instituto de Desarrollo Regional, Universidad de Sevilla, Excma. Diputación de Cádiz. 450pp.

Van Soest P. J. (1967) Development of a comprehensive system of feed analyses and its application to forages. *J. Anim. Sci.* **26**, 119-127.

Vaudo, A. D., Tooker, J. F., Grozinger, C. M. and Patch, H. M. (2015). Bee nutrition and floral resource restoration. *Curr. Opin. Insect Sci*. **10**, 133-141.

Vergoz V, Roussel E, Sandoz J-C, Giurfa M (2007) Aversive Learning in Honeybees Revealed by the Olfactory Conditioning of the Sting Extension Reflex. PLoS ONE 2(3): e288.

Von Der Ohe, W., Persano Oddo, L., Piana, L., Morlot, M. and Martin, P. (2004). Harmonized methods of melissopalynology. *Apidologie* **35** (Special issue): S18–S25.

von Frisch, K. (1967). The dance language and orientation of bees. Cambridge, MA, US: Harvard University Press.

Waser, N. M., Chittka, L., Price, M. V., Williams, N. M. and Ollerton, J. (1996). Generalization in pollination systems, and why it matters. *Ecology* **77**(4), 1043-1060.

Wehner, R. (1967). The physiology of form vision in the honeybee. *Z. Vgl. Physiol.* **55**, 145-166.

Wehner, R. (1971). The generalization of directional visual stimuli in the honey bee, *Apis mellifera*. *J. Insect Physiol* **17**, 1579-1591.

Winston, M. L. (1987). The Biology of the Honey Bee. Boston: Harvard University Press. 281pp.

Wright, G. A. and Schiestl, F. P. (2009). The evolution of floral scent: the influence of olfactory learning by insect pollinators on the honest signalling of floral rewards. *Funct. Ecol* **23** (5), 841-851.

Wright, G. A. and Smith, B. H. (2003). Variation in complex olfactory stimuli and its influence on odour recognition. *Proc. R. Soc. Lond. B* **271**, 147-152.

Wright, G. A., Kottcamp, S. M. and Thomson, M. G. A. (2008). Generalization mediates sensitivity to complex odor features in the honeybee. PLoS ONE 3(2): e1704. DOI:10.1371/journal.pone.0001704.

Figures

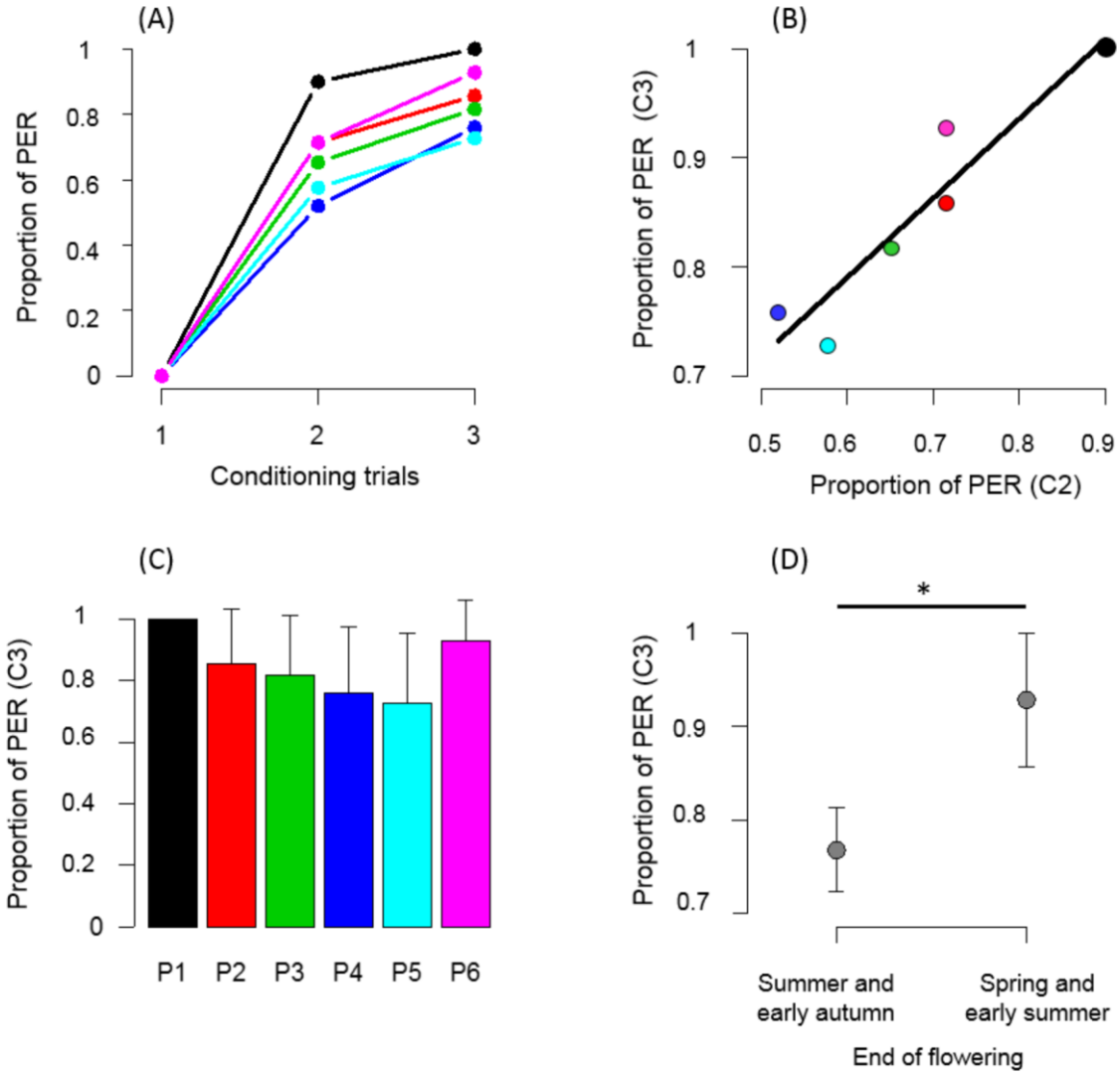


Figure 1. Behavioral responses of honey bees during the *Conditioning* phase. A) C*onditioning* phase. Proportion of PER success to each type of pollen in each conditioning trial (Pollen 1 *n*=28, Pollen 2 *n*=39, Pollen 3 *n*= 47, Pollen 4 *n*=64, Pollen 5 *n*=29, Pollen 6 *n*=30). B) Pearson's correlation between the proportion of PER of C2 and C3. There was a significant correlation between the variables (Pearson's rank correlation coefficient r_P=0.938). C) Proportion of PER for each type of pollen at C3. The vertical lines indicate the standard error. There were no significant differences between pollen types. D) Analysis of Variance which showed the effect of two periods of flowering on the proportion of PER at C3. The asterisk indicates significant differences (with * < 0.05). The average values are showed and the vertical lines indicate the standard error.

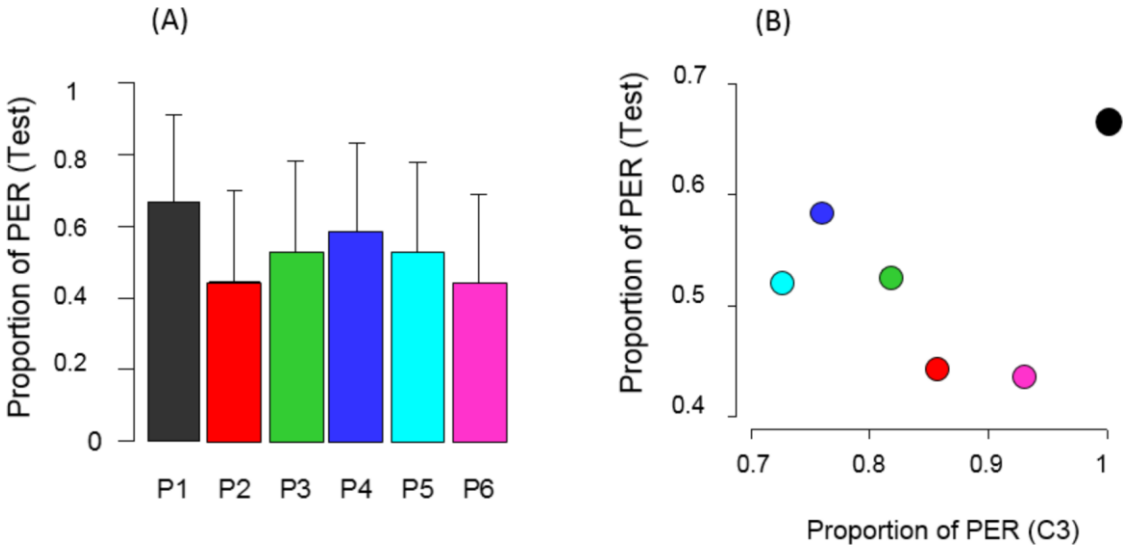


Figure 2. Behavioral responses of honey bees during the *Test* phase. A) Proportion of PER for each type of pollen in those trials in which bees were conditioned and tested with the same type of pollen (Pollen 1 n=15, Pollen 2 n=18, Pollen 3 n= 38, Pollen 4 n=48, Pollen 5 n=23, Pollen 6 n=23). The vertical lines indicate the standard error. There were no significant differences for the behavioral responses between pollen types. B) Pearson's correlation between the proportion of PER at C3 and *Test*. There was no correlation between the variables (Pearson's rank correlation coefficient r_P = 0.195).

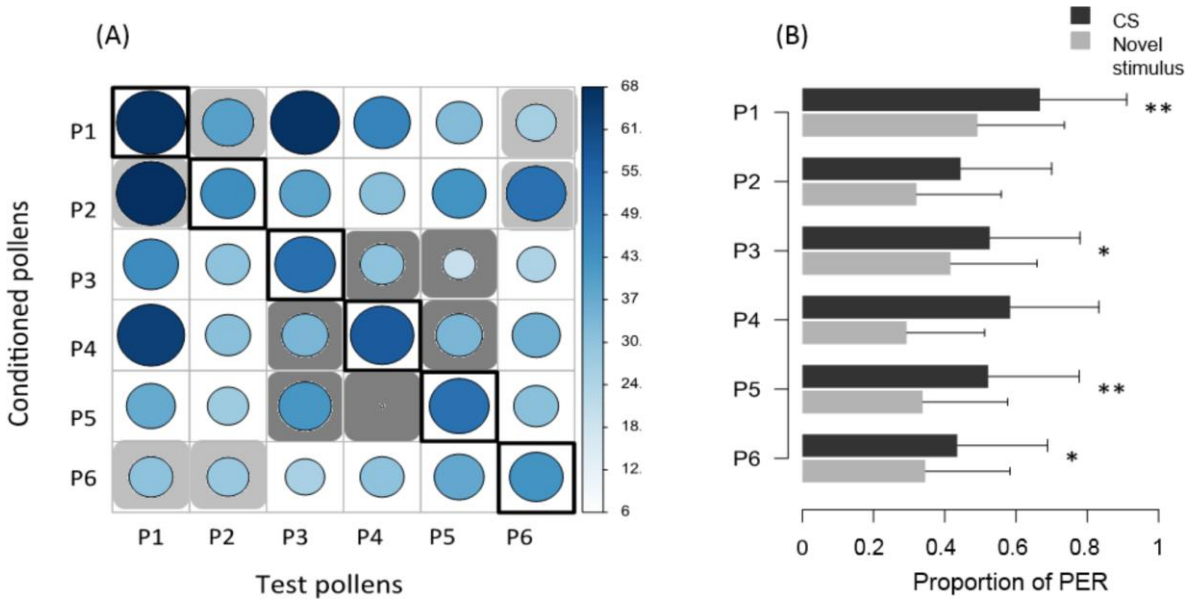
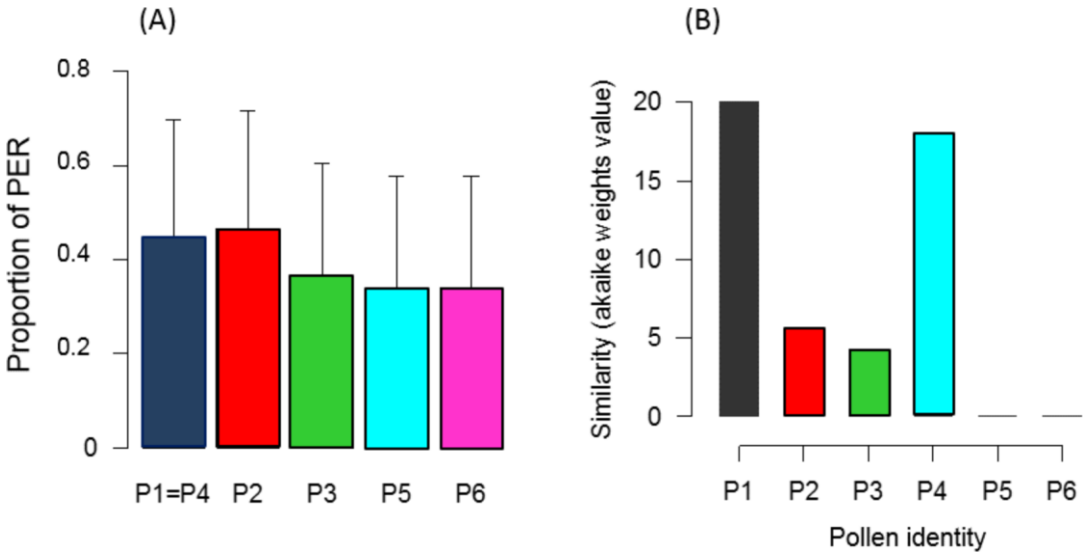


Figure 3. Generalization matrix which relates the level of PER at *Conditioning* to the level of PER at *Test* for each combination of pollen types. A) The perception matrix represents the mean value of PER success during the *Conditioning vs. Test* (*n* = 237). Dark blue= maximal response; White= minimal response. Light gray background: Flowering ends in Spring and early Summer; dark gray background: Flowering ends in Summer and early Autumn. B) Proportion of PER between both phases for each type of pollen. The black bars represent the PER success in those trials in which we always used the same pollen in both phases (CS), while the gray bars indicate the PER success of the trials in which a different pollen was used in the Test phase (Novel stimulus). The horizontal lines indicate the standard error. The asterisk indicates significance of binomial GLM with * <0.05; ** <0.01.



Figures 4. Perception of pollen similarity based on the selected model. A) Proportion of PER (*Conditioning* and *Test*) for each pollen type, and assumed P1=P4. There were no significant differences. The average values are showed and the vertical lines indicate the standard error. B) Similarity value estimated by Akaike weights values.

TABLES

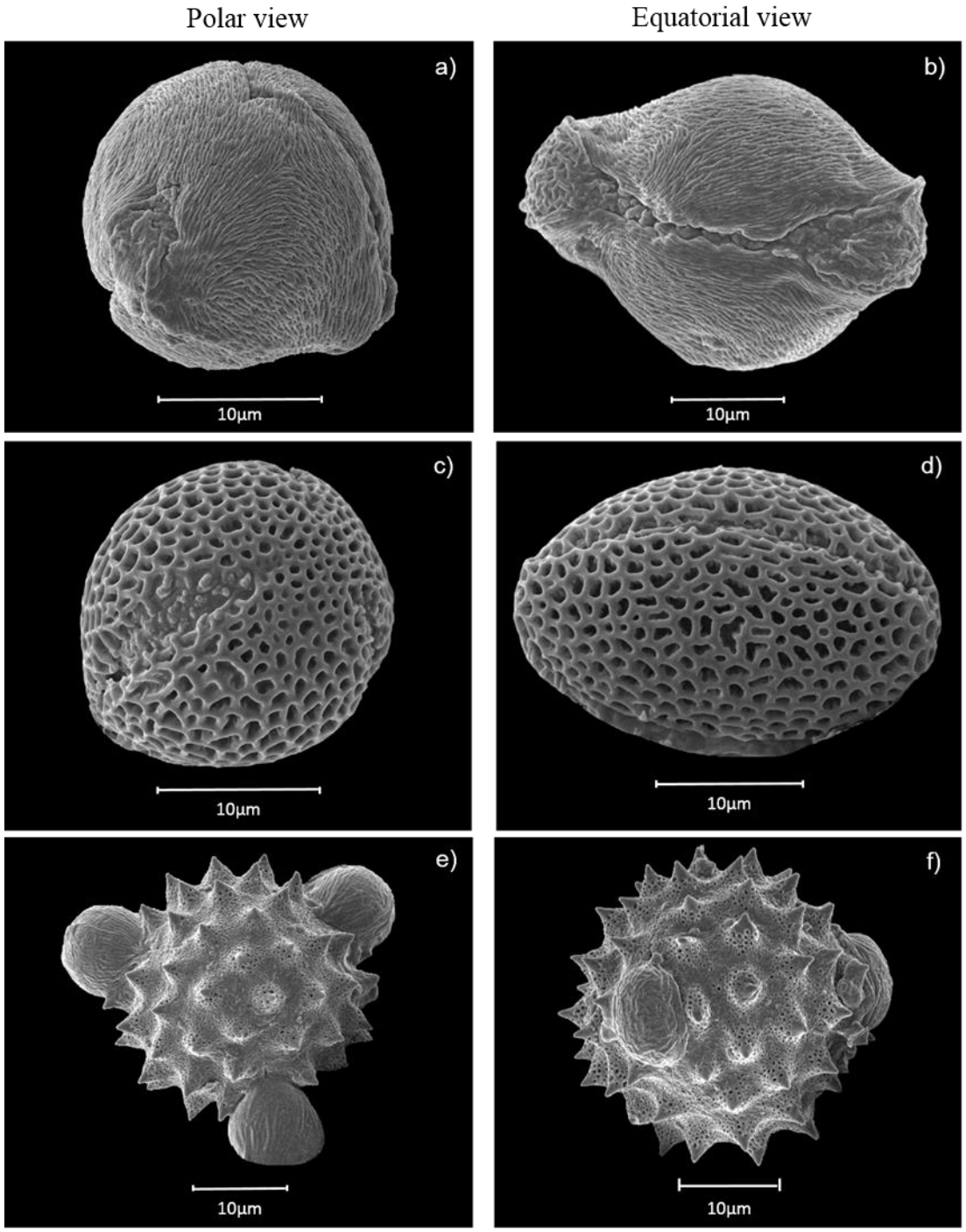
Table 1. Analysis of variance (ANOVA) to determine the effect of pollen characteristics on the level of PER during the *Conditioning* phase. The asterisk indicates significant differences (P<0.05). Degrees of freedom = 1 for each model run.

Pollen characteristics	*F* value	*P* value
End of flowering	10.86	0.030*
Grain size	0.38	0.569
Taxonomical family	0.84	0.410
Protein amount	0.21	0.667

Table 2. Analysis of variance (ANOVA) to determine the effect of pollen characteristics on the level of PER during *Test* phase. The evaluated characteristics show no effect on the behavioral response of bees (P>0.260). Degrees of freedom = 1 for each model run.

Pollen characteristics	*F* value	*P* value
End of flowering	0.13	0.734
Grain size	0.14	0.723
Taxonomical family	1.59	0.275
Protein amount	1.71	0.260

Figure S1- Palynological identification of the pollen pellet morphospecies (PPMs). a-b) *Pyracantha coccinea* (Rosales: Rosaceae); c-d) *Capsella bursa-pastoris* (Brassicales: Brassicaceae); e-f) *Carduus thoermeri* (Asterales: Asteraceae); g-h) *Hypochaeris radicata* (Asterales: Asteraceae); i-j) *Diplotaxis tenuifolia* (Brassicales: Brassicaceae); k-l) *Salix humboldtiana* (Malpighiales: Salicaceae).



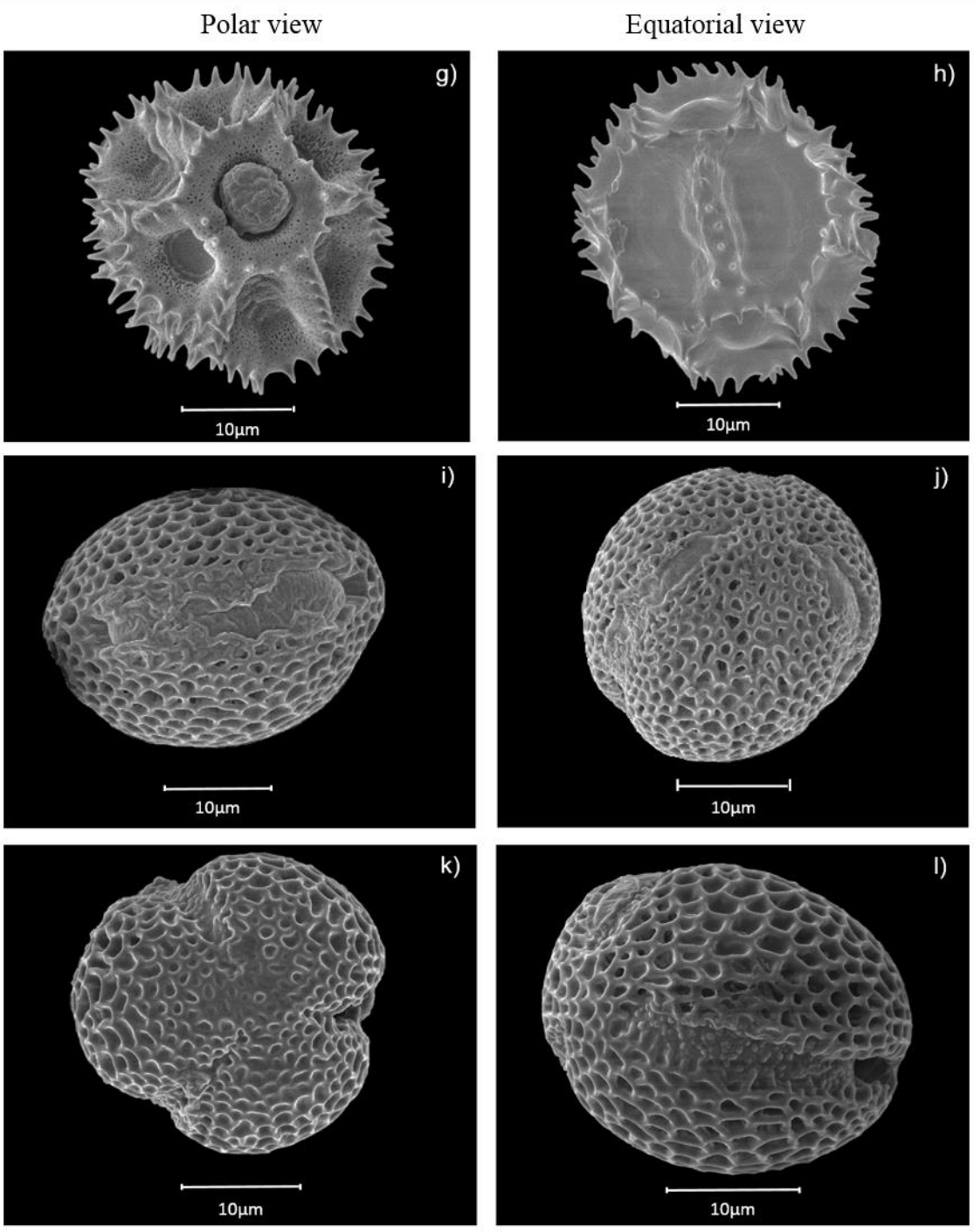


Figure S2. Detailed process of one conditioning and control stage - CS (Conditioned Stimulus); US (Unconditioned Stimulus).

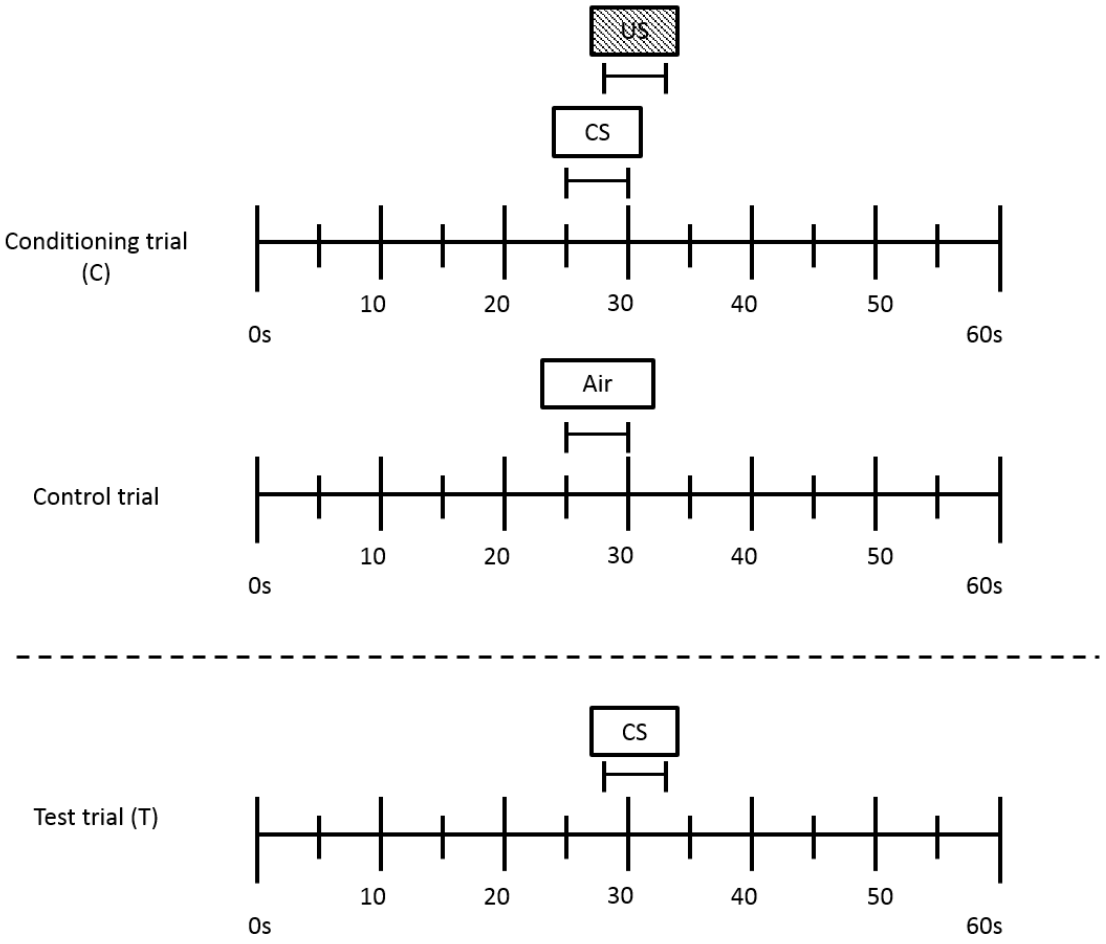


Figure S3. Repartition among the pollen conditioned classes of the bees excluded (*n*=13) of the statistics due to their positive PER at the first trial.

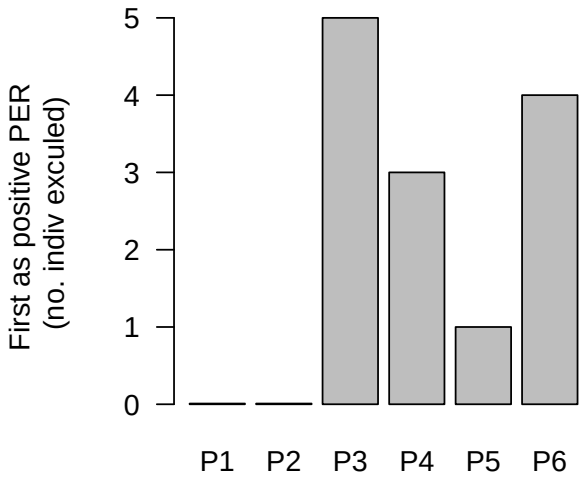


Figure S4. Colinearity test between explanatory variables fitted using the *chart.Correlation* function of the *Performance Analytics* R-package. Values represent Pearson correlation coefficient. Red lines fit a polynomial surface determined by one or more numerical predictors, using local fitting. There is no significant correlations between explanatory variables meaning a control if the colinearity test.

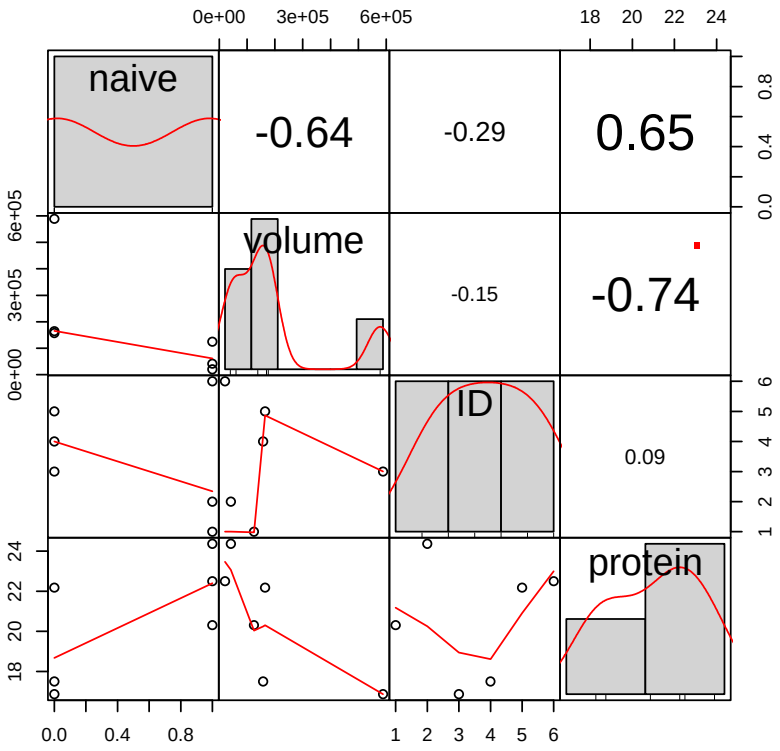


Table S1. Pollens and plants characteristics.

Pollen	Scientific name	Pollen description	Polar axis (P) and Equatorial diameter (E) (µm)	Color	Maximum flowering	Habit	%Protein content (6.25*Nitrogen amount)
1	*Pyracantha coccinea* (Rosales: Rosaceae)	Monad with three colporus, isopolar and radial symmetry. In polar view is circular while in equatorial view is elliptical. Streaked surface, short striae in irregular arrangement.	P=36-41 E=30-32	Pale yellow	Nov-Dec.	Exotic perennial tree	20.31
2	*Capsella bursa-pastoris* (Brassicales: Brassicaceae)	Monad, with three colpus with granular membrane, isopolar and radially symmetric. In polar view is circular and lobulated while in equatorial vision is circular or elliptical. The surface is reticulated.	P=14-39 E=13-30	Strong yellow	Nov-Dec	Exotic herb	24.37
3	*Carduus thoermeri* (Asterales: Asteraceae)	Monad, large size, spherical or slightly ellipsoidal. Tricolporate. Spines from 5 to 7 µm high, broad base. The entire surface with small perforations.	P=43-52 E=49-55	Dark purple	Nov-March	Exotic herb	16.87
4	*Hypochaeris radicata* (Asterales: Asteraceae)	Monad, tricolporate and echinate. The shape of pollen in polar and equatorial view is circular with hexagonal ambit.	P=27-32 E=30-37	Strong orange	Nov-Feb	Exotic herb	17.5
5	*Diplotaxis tenuifolia* (Brassicales: Brassicaceae)	Monad, radial symmetry. Tricolpates. In polar view are circular while in equatorial view are circular or elliptical. Reticular surface, long colpi, wide grooves without continuous margins formed by the meshes of the reticulum	P=35-42 E=32-36	Yellow	Jan-Feb	Exotic herb	22.18
6	*Salix humboldtiana* (Malpighiales: Salicaceae)	Monad, in polar view is circular or mildly triangular, while is circular in equatorial view. Reticulated surface. Tricolpates, long colpi with granular membrane.	P=18-22 E=15-19	Yellow	Sep-Nov	Native deciduous tree	22.5

Table S2. Values of statistical parameters obtained when analyzing the % PER in Conditioning 3 (C3) by mean of a GLM.

	Estimate	Std. Error	*Z* value	*P* value
P2-P1	-16.774	1190.865	-0.014	0.997
P3-P1	-17.074	1190.865	-0.014	0.997
P4-P1	-17.413	1190.865	-0.015	0.996
P5-P1	-17.585	1190.865	-0.015	0.996
P6-P1	-16.001	1190.865	-0.013	0.996
P3-P2	-0.300	0.607	-0.494	0.995
P4-P2	-0.639	0.553	-1.154	0.825
P5-P2	-0.810	0.621	-1.305	0.738
P6-P2	0.773	0.878	0.880	0.937
P4-P3	-0.339	0.457	-0.741	0.970
P5-P3	-0.510	0.537	-0.950	0.915
P6-P3	1.073	0.821	1.307	0.737
P5-P4	-0.171	0.475	-0.362	0.999
P6-P4	1.412	0.782	1.806	0.402
P6-P5	1.584	0.831	1.905	0.342

Table S3. Values of statistical parameters obtained when analyzing the % PER during the Test by mean of a GLM.

	Estimate	Std. Error	*Z* value	*P* value
P2-P1	0.002	0.288	0.008	0.996
P3-P1	-0.402	0.274	-1.468	0.682
P4-P1	-0.038	0.258	-0.148	0.992
P5-P1	-0.550	0.290	-1.897	0.400
P6-P1	-0.563	0.297	-1.895	0.401
P3-P2	-0.404	0.253	-1.597	0.597
P4-P2	-0.040	0.235	-0.171	0.991
P5-P2	-0.552	0.271	-2.037	0.318
P6-P2	-0.565	0.279	-2.025	0.324
P4-P3	0.364	0.212	1.713	0.519
P5-P3	-0.148	0.255	-0.580	0.992
P6-P3	-0.161	0.264	-0.609	0.990
P5-P4	-0.512	0.239	-2.138	0.264
P6-P4	-0.525	0.249	-2.102	0.283
P6-P5	-0.012	0.280	-0.045	0.995

Table S4- Proportion of PER success for the perception matrix. With parentheses the total n values for each combination

		Test pollens					
		P1	P2	P3	P4	P5	P6
Conditioned pollens	P1	0.66 (n=21)	0.47 (n=21)	0.57 (n=21)	0.42 (n=21)	0.29 (n=17)	0.29 (n=17)
	P2	0.73 (n=19)	0.52 (n=19)	0.42 (n=19)	0.42 (n=19)	0.40 (n=25)	0.52 (n=25)
	P3	0.5 (n=28)	0.46 (n=28)	0.64 (n=37)	0.42 (n=28)	0.21 (n=19)	0.21 (n=19)
	P4	0.67 (n=37)	0.40 (n=40)	0.43 (n=39)	0.69 (n=39)	0.38 (n=26)	0.38 (n=29)
	P5	0.37 (n=16)	0.43 (n=16)	0.47 (n=19)	0.12 (n=16)	0.63 (n=22)	0.48 (n=23)
	P6	0.33 (n=18)	0.33 (n=18)	0.36 (n=19)	0.31 (n=19)	0.38 (n=21)	0.52 (n=25)

Table S5. Matrix of simplification listing the 56 scenarios of renamed pollen identity. The first scenario (sc1) represents the original affiliation of the pollen identity (i.e. the six pollen types are differentiated), and the other scenarios are simplified. The simplification means a restriction of the number of pollen identities (i.e. <6). The scenarios from sc2 to sc16 include five renamed pollen identities (A, B, C, D and E) with all the combination of identity allocation. The scenarios from sc17 to sc35 include four renamed pollen identities (A, B, C and D) with all the combination of identity allocation. The scenarios from sc36 to sc49 include three renamed pollen identities (A, B and C) with all the combination of identity allocation. The scenarios from sc50 to sc56 include two renamed pollen identities (A and B) with all the combination of identity allocation.

Scenario	***P1***	***P2***	***P3***	***P4***	***P5***	***P6***
sc1	A	B	C	D	E	F
sc2	A	A	B	C	D	E
sc3	A	B	A	C	D	E
sc4	A	B	C	A	D	E
sc5	A	B	C	D	A	E
sc6	A	B	C	D	E	A
sc7	A	B	B	C	D	E
sc8	A	B	C	B	D	E
sc9	A	B	C	D	B	E
sc10	A	B	C	D	E	B
sc11	A	B	C	C	D	E
sc12	A	B	C	D	C	E
sc13	A	B	C	D	E	C
sc14	A	B	C	D	D	E
sc15	A	B	C	D	E	D
sc16	A	B	C	D	E	E
sc17	A	A	A	B	C	D
sc18	A	A	B	A	C	D
sc19	A	A	B	C	A	D
sc20	A	A	B	C	D	A
sc21	A	B	A	A	C	D
sc22	A	B	A	C	A	D

sc23	A	B	A	C	D	A
sc24	A	B	C	A	A	D
sc25	A	B	C	D	A	A
sc26	A	B	B	B	C	D
sc27	A	B	B	C	B	D
sc28	A	B	B	C	D	B
sc29	A	B	C	B	B	D
sc30	A	B	C	B	D	B
sc31	A	B	C	D	B	B
sc32	A	B	C	C	C	D
sc33	A	B	C	C	D	C
sc34	A	B	C	D	C	C
sc35	A	B	C	D	D	D
sc36	A	A	A	A	B	C
sc37	A	A	A	B	A	C
sc38	A	A	A	B	B	A
sc39	A	B	A	A	A	C
sc40	A	B	A	C	A	A
sc41	A	B	C	A	A	A
sc42	A	A	B	C	A	A
sc43	A	A	B	A	C	A
sc44	A	A	B	A	A	C
sc45	A	B	B	B	B	C
sc46	A	B	B	B	C	B
sc47	A	B	B	C	B	B
sc48	A	B	C	B	B	B
sc49	A	B	C	C	C	C
sc50	A	A	A	A	A	B
sc51	A	A	A	A	B	A
sc52	A	A	A	B	A	A
sc53	A	A	B	A	A	A
sc54	A	B	A	A	A	A
sc55	A	B	B	B	B	B
sc56	A	A	A	A	A	A

Table S6. List of models developed for determine the generalization between pollen types. The Akaike Information Criterion (AIC) was used for ranking the binomial generalized linear models. The best model (Δ AIC < 2) is presented in blue while the null model is presented in red. Across the 56 concurrent models, five models was retained in the top-model set with a Δ AIC < 10 (in bold). Letters (A-F) indicate the sequence of combinations. *i* = for model *I*; Δ*i* (AIC) = [AIC*i* – min(AIC)]

Model rank *i*	**Pollen identity replacement**						**Intercept *i***	**Estimate *i***	**Std. Error *i***	**Z score *i***	**P value *i***	**AIC *i***	**Δ*i* (AIC)**
	P1	*P2*	*P3*	*P4*	*P5*	*P6*							
1	**A**	**B**	**C**	**A**	**D**	**E**	**-0.665**	**0.858**	**0.163**	**5.273**	**1.34e-07**	**1133.162**	**0**
2	**A**	**A**	**B**	**A**	**C**	**D**	**-0.705**	**0.701**	**0.149**	**4.719**	**2.37e-06**	**1138.885**	**5.723**
3	**A**	**B**	**A**	**A**	**C**	**D**	**-0.709**	**0.683**	**0.146**	**4.664**	**3.09e-06**	**1139.469**	**6.307**
4	**A**	**A**	**B**	**C**	**D**	**E**	**-0.605**	**0.746**	**0.169**	**4.423**	**9.75e-06**	**1141.731**	**8.569**
5	**A**	**B**	**A**	**C**	**D**	**E**	**-0.606**	**0.718**	**0.165**	**4.34**	**1.42e-05**	**1142.505**	**9.343**
6	A	A	A	B	C	D	-0.642	0.644	0.152	4.246	2.18e-05	1143.338	10.176
7	A	A	A	A	B	C	-0.779	0.611	0.149	4.102	4.09e-05	1144.305	11.143
8	A	B	C	D	E	F	-0.567	0.688	0.179	3.834	0.00012	1146.71	13.548
9	A	A	B	A	C	A	-0.727	0.549	0.144	3.81	0.00014	1146.799	13.637
10	A	B	C	D	E	B	-0.575	0.602	0.166	3.631	0.00028	1148.308	15.146
11	A	A	B	C	D	A	-0.597	0.543	0.153	3.557	0.00038	1148.857	15.695
12	A	B	C	A	A	D	-0.624	0.517	0.148	3.492	0.00048	1149.292	16.13
13	A	A	B	C	A	D	-0.596	0.528	0.152	3.474	0.00051	1149.438	16.276
14	A	B	C	D	A	E	-0.56	0.552	0.167	3.299	0.00100	1150.625	17.463
15	A	B	C	D	B	E	-0.56	0.537	0.165	3.25	0.00115	1150.961	17.799
16	A	B	A	C	A	D	-0.592	0.487	0.151	3.223	0.00127	1151.108	17.946
17	A	B	C	D	E	D	-0.575	0.518	0.164	3.154	0.00161	1151.538	18.376
18	A	A	A	B	A	C	-0.629	0.434	0.143	3.028	0.00246	1152.31	19.148
19	A	B	C	D	C	E	-0.557	0.504	0.166	3.028	0.00246	1152.343	19.181
20	A	B	C	D	E	A	-0.547	0.505	0.168	3.01	0.00261	1152.471	19.309
21	A	B	C	D	E	E	-0.552	0.49	0.163	3.01	0.00261	1152.478	19.316
22	A	A	B	A	A	C	-0.657	0.427	0.143	2.983	0.00286	1152.568	19.406
23	A	B	B	C	D	E	-0.55	0.49	0.164	2.994	0.00275	1152.57	19.408
24	A	A	A	A	B	A	-0.82	0.508	0.173	2.938	0.00330	1152.626	19.464
25	A	B	A	A	A	C	-0.654	0.401	0.144	2.788	0.00530	1153.692	20.53
26	A	B	C	D	E	C	-0.544	0.452	0.166	2.717	0.00658	1154.141	20.979
27	A	B	B	B	B	B	-0.083	-0.448	0.166	-2.707	0.00679	1154.236	21.074
28	A	B	A	C	D	A	-0.563	0.404	0.151	2.673	0.00753	1154.384	21.222
29	A	B	C	D	B	B	-0.557	0.379	0.149	2.538	0.01116	1155.103	21.941
30	A	B	C	B	D	E	-0.542	0.398	0.159	2.511	0.01204	1155.232	22.07

31	A	B	C	C	D	E	-0.542	0.391	0.157	2.49	0.01276	1155.34	22.178
32	A	A	B	C	A	A	-0.579	0.341	0.144	2.375	0.01756	1155.889	22.727
33	A	A	A	A	A	B	-0.728	0.391	0.171	2.289	0.02210	1156.19	23.028
34	A	B	C	D	D	E	-0.529	0.372	0.164	2.275	0.02290	1156.368	23.206
35	A	B	C	A	A	A	-0.589	0.299	0.143	2.091	0.03657	1157.144	23.982
36	A	B	C	B	D	B	-0.55	0.3	0.147	2.044	0.04100	1157.352	24.19
37	A	B	B	C	D	B	-0.533	0.302	0.15	2.018	0.04357	1157.465	24.303
38	A	B	C	D	A	A	-0.525	0.3	0.151	1.978	0.04791	1157.629	24.467
39	A	A	B	A	A	A	-0.659	0.314	0.16	1.964	0.04959	1157.631	24.469
40	A	B	B	C	B	D	-0.53	0.292	0.149	1.956	0.05050	1157.714	24.552
41	A	A	A	B	B	A	-0.557	0.246	0.142	1.726	0.08431	1158.549	25.387
42	A	B	C	D	C	C	-0.51	0.224	0.15	1.491	0.13606	1159.312	26.15
43	A	A	A	B	A	A	-0.57	0.221	0.151	1.463	0.14355	1159.383	26.221
44	A	A	A	A	A	A	-0.52	0.193	0.143	1.352	0.17628	1159.533	26.371
45	A	B	A	C	A	A	-0.504	0.187	0.148	1.261	0.20713	1159.703	26.541
46	A	B	C	D	D	D	-0.505	0.18	0.147	1.228	0.21958	1159.94	26.778
47	A	B	C	C	D	C	-0.489	0.141	0.144	0.981	0.32645	1160.025	26.863
48	A	B	B	B	C	D	-0.482	0.133	0.146	0.911	0.36252	1160.568	27.406
49	A	B	C	B	B	D	-0.54	0.144	0.163	0.883	0.37713	1160.705	27.543
50	A	B	A	A	A	A	-0.362	-0.124	0.143	-0.867	0.38586	1160.749	27.587
51	A	B	B	B	B	C	-0.364	-0.117	0.143	-0.82	0.41209	1160.782	27.62
52	A	B	C	C	C	C	-0.481	0.104	0.142	0.732	0.46390	1160.861	27.699
53	A	B	B	C	B	B	-0.472	0.103	0.146	0.707	0.47969	1160.995	27.833
54	A	B	C	C	C	D	-0.445	0.026	0.142	0.18	0.85691	1161.034	27.872
55	A	B	C	B	B	B	-0.429	-0.005	0.143	-0.033	0.97376	1161.5	28.338
56	A	B	B	B	C	B	-0.413	-0.007	0.144	0.007	0.98650	1161.532	28.37

Table S7- Values of statistical parameters obtained when analyzing the total % PER for each pollen type (assuming P1=P4) by mean of a GLM. These results are represented in Figure 5a.

	Estimate	Std. Error	*Z* value	*P* value
P2-(P1=P4)	0.029	0.223	0.131	0.997
P3-(P1=P4)	-0.037	0.200	-1.871	0.327
P5-(P1=P4)	-0.523	0.226	-2.308	0.139
P6-(P1=P4)	-0.536	0.237	-2.265	0.153
P3-P2	-0.403	0.253	-1.594	0.495
P5-P2	-0.552	0.271	-2.038	0.243
P6-P2	-0.565	0.279	-2.027	0.248
P5-P3	-0.149	0.255	-0.583	0.977
P6-P3	-0.162	0.264	-0.613	0.972
P6-P5	-0.013	0.280	-0.046	0.995