

1 **Effects of neonicotinoid exposure on molecular and physiological indicators of honey bee**
2 **immunocompetence**

3 Elizabeth J. COLLISON^{1,2}, Heather HIRD¹, Charles R. TYLER², James E. CRESSWELL²

4 ¹ Fera, Sand Hutton, York, YO41 1LZ, UK

5 ² Biosciences, College of Life and Environmental Sciences, University of Exeter, Geoffrey Pope,
6 Stocker Road, Exeter, EX4 4QD, UK

7 Corresponding author: E.J. Collison, Present address: elizabeth.collison@tsgeconsulting.com

8

9 **Short title:** Neonicotinoid effects on immunocompetence

10

1 **Abstract-** Bee declines have been associated with various stressors including pesticides and
2 pathogens. We separately exposed immune-challenged adult worker honey bees (*Apis mellifera*
3 L.) to two neonicotinoid pesticides, thiamethoxam (10 ppb) and imidacloprid (102 ppb), by
4 dietary delivery. We found that whereas neonicotinoid exposure weakly affected transcriptional
5 responses of antimicrobial genes, it did not detectably affect the physiological antimicrobial
6 response as measured by a lytic clearance assay of haemolymph. Our findings add to the
7 evidence that transcriptional responses in immune-related genes are not yet reliable indicators of
8 pesticide impacts on bee health, which suggests caution in their future use as biomarkers in
9 pesticide risk assessment.

10

11 **imidacloprid/ thiamethoxam/ immunocompetence/ antimicrobial peptide/ gene expression**

12

13 **1. INTRODUCTION**

14 There is widespread concern over losses of managed honey bees (*Apis mellifera* L.) but
15 appropriate responses are unclear because a complex of multiple stressors is likely to be
16 responsible for the observed decline in bee health (Potts et al. 2010). Therefore recent studies
17 have been conducted in an effort to investigate the potential interactions among stressors and
18 their effects on various biological systems of honey bees. In particular, there is growing interest
19 in the interactive effects of pesticide exposure and pathogen infection in bees (reviewed by
20 Collison et al. 2016). The European Food Safety Authority (EFSA) Panel on Plant Protection
21 Products and their Residues (PPR) recently recommended that further work is required to
22 identify the molecular basis of interactions between exposure to pesticides and the range of
23 diseases in the honey bee (EFSA 2012). Further, EFSA recommended the development of

1 physiological and molecular biomarkers as diagnostic tools that could be valuable in improving
2 risk assessment procedures for determining the effects of pesticides on bees. To better
3 understand the mechanisms underlying disease-pesticide interactions, recent studies have been
4 conducted in an effort to investigate the effects of pesticide exposure on bee immunocompetence
5 (the ability to mount an immune response), with particular focus on the neonicotinoid pesticides,
6 which have until recently been widely used in the protection of bee-attractive crops such as
7 oilseed rape (*Brassica napus* L.).

8 The immune response in individual honey bees consists primarily of cellular responses, such as
9 phagocytosis and encapsulation, and humoral responses *via* the prophenoloxidase cascade
10 (leading to melanisation) and antimicrobial effectors (Evans et al. 2006). The expression of some
11 genes related to these immune processes has been found to change following neonicotinoid
12 exposure, but with no apparent consistency. For example, dietary exposure to imidacloprid led to
13 increased transcription of the antimicrobial effector abaecin in larval honey bees in one study
14 (Derecka et al. 2013), but not in another (Gregorc et al. 2012). In adult honey bees, by contrast,
15 neonicotinoid exposure reduced transcription in a different antimicrobial effector, apidaecin (Di
16 Prisco et al. 2013). Neonicotinoid exposure also causes detectable effects at the physiological
17 level (Brandt et al. 2016), but again with little apparent consistency (Alaux et al. 2010a). Overall,
18 therefore, it remains unclear whether neonicotinoid-induced changes in the transcription of
19 immune genes consistently indicate the levels of immunocompetence that are realised at the
20 physiological level. Previously, few studies have been conducted to test for these corresponding
21 effects at both the molecular and the physiological level using both a common exposure scenario
22 and common immune-related endpoints. Consequently, the extent to which the different
23 components of the immune response react in concert to neonicotinoid exposure has been unclear.

1 Potentially, some of the non-correspondence between gene expression and physiological
2 responses may have arisen because the studies to date have collected measurements at only a
3 single sampling point in time, but insect immune studies have demonstrated the importance of
4 temporality in the response to immune challenge (e.g. Gättschenberger et al. 2013, Korner and
5 Schmid-Hempel 2004, Riddell et al. 2011). In summary, there is a need to investigate how
6 neonicotinoid pesticides affect immunocompetence in honey bees and whether such an impact
7 can be reliably detected by examination of molecular responses.

8 To begin to address this need, we investigated the effect of dietary neonicotinoids on the
9 antimicrobial peptide (AMP) component of the honey bee immune response. We carried out a
10 series of laboratory experiments investigating temporal correspondences between changes in
11 gene expression and measures of physiological AMP activity following exposure to either
12 imidacloprid or thiamethoxam. Besides testing the impact of these neonicotinoids on
13 physiological indicators of immunocompetence, our study enabled us to evaluate gene
14 expression as a biomarker of pesticide effects on bee health.

15 We investigated the effects of two neonicotinoid insecticides that have been widely used in crop
16 protection: imidacloprid and thiamethoxam. In Europe and North America, imidacloprid has
17 been replaced in normal agricultural practice by other neonicotinoids, such as thiamethoxam.
18 Imidacloprid is nevertheless of interest because it has been the most commonly tested subject in
19 ecotoxicological investigations of neonicotinoid impacts on bees. For our investigation, we
20 tested the effect of a dietary concentration (102 parts per billion, ppb) that is much higher than
21 environmentally realistic levels (<10 ppb), because we wanted to improve the chance of
22 detecting the response to intoxication. By contrast, in our experiment on thiamethoxam, we used
23 a dietary dose (10 ppb) that exposed bees to environmentally realistic residue levels (e.g 11 ppb

1 in nectar observed by Stoner and Eitzer 2012) as any findings made relative to this dose may
2 have greater ecological relevance.

3 Each study was designed as a fully factorial experiment in which two levels of the pesticide
4 (absent, present) were combined with three levels of immune-challenge (see below). Our
5 approach principally aimed to both elucidate the effects of pesticide exposure on immune
6 responses and to test the correspondence of molecular and physiological immune endpoints. We
7 did not set out to establish dose-dependent effects or to determine threshold levels of toxicity
8 (e.g. NOECs).

9 In order to stimulate the immune system of honey bees experimentally, we employed an artificial
10 immune challenge *via* an injection with lipopolysaccharides (LPS) from *Escherichia coli* to
11 mimic a bacterial-like infection. This approach was adopted to standardise the stimulus and to
12 avoid the variation inherent in using a real pathogen, which can be logistically difficult to
13 control. The present study, therefore, does not aim to investigate the biological mechanisms
14 associated with any specific natural infection, but instead seeks to understand better the
15 fundamental relationships between the temporal dynamics of transcriptional and physiological
16 changes using a well-established method for insect immune studies.

17 **2. MATERIALS AND METHODS**

18 We exposed newly emerged adult worker honey bees to either un-dosed control or
19 neonicotinoid-spiked sucrose feeders and imposed an immune challenge after five days of
20 experimental feeding. While maintaining bees on the same dietary treatment, we collected
21 samples for immune-related assays over the remainder of the experimental period. In separate
22 experiments, sample collection followed either a short time course of between 2 h and 48 h post
23 immune challenge (PIC) or a longer time course of between 24 h and 168 h (1-7 d) PIC. Samples

1 were analysed either for expression levels of six AMP genes or for levels of antimicrobial
2 activity at a physiological (enzymatic) level (Table I, see also supplementary material for an
3 overall setup of treatment and sampling combinations).

4 Across all experiments, individual cages (i.e. and all bees within each cage) were randomly
5 assigned to a specific sampling time point and sample type at the start of the experiment (with a
6 total of three cages per treatment/time point combination). No repeated measures were taken, and
7 all cages contained the same number of bees (10) throughout the experimental period, unless
8 mortality occurred. Six bees within a cage were pooled for immune measurements (as discussed
9 below) and each cage was treated as a biological replicate (giving a total of three replicates for
10 each treatment/time point combination).

11 For details of data analysis, see supplementary material.

12 **2.1. Honey bee provenance and husbandry**

13 All honey bees were from colonies of British hybrid bees maintained on the home apiary at the
14 Food and Environment Research Agency, Sand Hutton, York, UK. Visual inspections of these
15 colonies showed no symptoms of disease or parasitic infection, but baseline levels of pathogens
16 cannot be ruled out. Further confirmation of pathogen levels (e.g. *via* PCR) in tested bees or their
17 colonies was not performed. Brood frames were collected from colonies between April and
18 September (2013, 2014) and placed in an environmental chamber (34 °C, 60 % relative
19 humidity, constant darkness; Sanyo Versatile Environmental Test Chamber). Workers were
20 collected from these frames as they emerged and batches of 10 workers were housed in modified
21 plastic cages (FK-RD8 clear PET containers; Ambican Ltd, London, UK). Each cage was
22 designed to allow the bees *ad libitum* access to a sucrose solution (50 % w/v) through a

1 punctured 1.5 mL microcentrifuge tube. Cages were maintained in the environmental chamber
2 throughout the experimental period (34 °C, 60 % relative humidity, constant darkness). The five
3 separate experiments described in Table I were each set up on a separate occasion between
4 August 2013 and June 2014 (no winter bees were used) and each used workers derived from a
5 single honey bee colony.

6 **2.2. Neonicotinoid exposure**

7 All of our experiments used chronic dietary exposures to sublethal concentrations of one
8 neonicotinoid, either imidacloprid or thiamethoxam. Stock solutions of neonicotinoids were
9 made in <0.1% acetone, and used to create the appropriate concentrations. In the imidacloprid
10 studies, the sucrose feeder syrup was spiked with 125 µg/L (= 102 ppb) imidacloprid (Fluka
11 Analytical 37894, Sigma-Aldrich, UK). In the thiamethoxam studies, the sucrose was spiked
12 with 12 µg/L (= 10 ppb) thiamethoxam (Fluka Analytical 37924, Sigma-Aldrich, UK).
13 Analytical verification of test concentrations was not conducted. All cages were designed to
14 allow bees to feed *ad libitum* from the sucrose feeder throughout the experiment. No other food
15 was provided. Control sucrose contained <0.1% acetone, equivalent to the volume of solvent
16 used in the neonicotinoid treatments. To quantify feeding rates, the feeder of each cage was
17 weighed every other day and corrected for evaporation using reference feeders kept in empty
18 cages. To quantify mortality rates, dead bees were recorded and removed every other day.

19 **2.3. Immune challenge**

20 Bees received one of three injection treatments, with all workers within a cage subjected to the
21 same treatment under ice-immobilisation (see supplementary material for further details). Bees in
22 the ‘LPS’ treatment group were injected with a 2 µL aliquot of 0.5 mg/mL LPS (Sigma L2755-

1 Lipopolysaccharides from *Escherichia coli* 0128:B12, Sigma-Aldrich, UK) dissolved in Insect
2 Ringer's solution (1:1:1 156 mM NaCl : 3 mM KCl : 2 mM CaCl₂). This same LPS
3 concentration has been widely used previously to elicit an immune response in honey bees
4 without any acute effects on survival (e.g. Alaux et al. 2012, Köhler et al. 2012, Laughton et al.
5 2011). Bees in the 'Ringer's' treatment group were injected with 2 µL Insect Ringer's solution to
6 control for any effects of the injection process itself. In the 'naïve' treatment, bees were ice-
7 immobilised but received no further treatment, which served as the unchallenged control.

8 **2.4. Measurement of gene expression**

9 At the designated time points, bees were placed directly into a freezer at -80 °C and stored until
10 RNA extraction. Total RNA was extracted from pooled homogenates of six bees (entire bodies)
11 from a single cage. For each feeding/injection treatment combination and time point, separate
12 homogenates from three cages were used as biological replicates for real-time quantitative PCR
13 (qPCR) analysis. Pooling of six bees per replicate homogenate served to minimise between-bee
14 variation in gene expression profiles. Following RNA extraction, cDNA was synthesised and the
15 relative expression of six AMP genes (abaecin, apidaecin, defensin-1, defensin-2, hymenoptaecin
16 and lysozyme-1) was measured using qPCR (supplementary material).

17 **2.5. Measurement of antimicrobial activity**

18 Haemolymph was collected from bees that had first been immobilised on ice. A small slit was
19 made in the abdominal tergites using sterile dissecting scissors and gentle pressure to the thorax
20 resulted in a bubble of haemolymph exiting this slit. An aliquot of 2-10 µL of this haemolymph
21 was collected with a pipette and immediately stored at -20 °C for later analysis. The
22 antimicrobial activity was separately measured in six individual bees from each single cage and

1 the cage mean was used as the biological replicate for statistical analysis. Three cages were
2 measured for each feeding/injection treatment combination and at each time point.

3 Antimicrobial activity was measured using a lysozyme clearance assay (Cotter et al. 2008) in
4 which antimicrobial proteins in the haemolymph lyse the peptidoglycan cell walls of the test
5 bacteria to produce a clear zone in a bacterial suspension, which is a proxy for relative
6 antimicrobial activity (a larger zone indicates greater antimicrobial activity). Phosphate buffer
7 solution (PBS) containing 1% agar was inoculated with 0.2 mg/mL lyophilised *Micrococcus*
8 *lycodeiiticus* (M3770; Sigma-Aldrich, UK). 8 mL of this suspension was poured immediately
9 into a 9 cm-diameter petri dish and left to set. Ten wells (approximately 2 mm diameter) were
10 bored on each plate. Each haemolymph sample was thawed on ice and a 2 μ L aliquot was added
11 per well. Plates were incubated at 27 °C for 72 h, and the diameters of clearance zones were
12 measured using digital callipers.

13 **3. RESULTS**

14 **3.1. Survival**

15 There were no evident effects of pesticide or injection treatments on honey bee behaviour and
16 activity. No treatment affected mortality, with the exception that Ringer's injection increased
17 mortality in Experiment E (Kruskal-Wallis: $\chi^2_{2df} = 7.57$, $P = 0.023$). In the short time course
18 experiments (2 d), between 2% and 7% of bees died and between 8% and 21% of bees died in
19 the longer time course experiments (7 d). The mortality rates were uniformly low across the
20 treatments including the controls, which indicates that the pesticide concentrations and immune
21 challenges used were essentially sublethal to worker honey bees.

22 **3.2. Gene expression**

1 In response to LPS injection, four antimicrobial effector genes (abaecin, apidaecin and defensin-
2 1 and hymenoptaecin) were significantly upregulated, but the immune challenge did not alter the
3 expression of defensin-2 and lysozyme-1 (Table II). A similar temporal pattern of expression
4 was observed for all four of the upregulated genes, despite between-gene differences in the
5 magnitude of changes in expression. Increased expression was typically observed as early as 2 h
6 PIC, increasing to peak expression at between 8 and 24 h PIC, after which the response showed a
7 gradual decline over the following six days (Fig. 1; see also Fig. S1-S5).

8 Exposure to imidacloprid was not found to alter expression of any of the six AMP genes tested
9 across the short or long time course experiments (Table II).

10 Exposure to thiamethoxam reduced the expression of abaecin dependent on the injection
11 treatment, but this effect was not seen in the longer time course study (Table II). Reduced
12 transcription of abaecin was most notable in response to thiamethoxam exposure 24 h post LPS-
13 injection (Fig. 1). Thiamethoxam exposure also had various effects on expression of apidaecin,
14 hymenoptaecin and lysozyme-1, but these effects were dependent on the time of sampling, and
15 only observed in the short time course experiment (Table II). Here, increased transcription of
16 apidaecin was observed following thiamethoxam exposure, most notably at 24 h post LPS-
17 injection (Fig. S1), whilst reduced transcription of hymenoptaecin was observed following
18 thiamethoxam exposure between 8 and 24 h PIC (Fig. S2) and the effects of thiamethoxam on
19 lysozyme-1 were transient (Fig. S5).

20 **3.3. Antimicrobial activity**

21 Antimicrobial activity at a physiological (enzymatic) level was significantly increased in
22 response to LPS injection in a time-dependent manner during both the short and long time course

1 experiments (Table II; Fig. 2). Ringer's injection also induced a response, but to a lesser extent
2 than in bees injected with LPS (Fig. 2). A peak in activity occurred between 24 and 72 h PIC,
3 followed by a gradual decline over the following days, and levels typically had not returned to
4 the baseline levels by the last sampling point 7 d PIC (Fig. 2).

5 No effects of exposure to either imidacloprid or thiamethoxam were observed on antimicrobial
6 activity in any of the experiments (Table II) and the temporal dynamics of the response to
7 injection were virtually identical in bees fed with control sucrose and those exposed to the
8 neonicotinoids (Fig. 2).

9 **3.4. Sucrose consumption**

10 Consumption of imidacloprid-spiked sucrose was significantly lower than the consumption of
11 control sucrose in all experiments (Table S2). In general, there were no significant differences in
12 consumption between bees feeding on control and thiamethoxam-spiked sucrose. The exception
13 to this was for bees in Experiment A, where there was significantly reduced feeding in the
14 thiamethoxam treatment (Table S2). Even when reduced feeding was observed in neonicotinoid-
15 treated bees, bees ingested substantial amounts of sucrose (e.g. in Experiment A, mean daily
16 sucrose consumption in the four days prior to immune challenge for control-fed: 46 ± 3 mg/bee;
17 for imidacloprid-fed: 38 ± 4 mg/bee; for thiamethoxam-fed bees: 36 ± 2 mg/bee) and consumed
18 substantial doses of neonicotinoid (3.0 ± 0.3 ng imidacloprid/bee; 2.8 ± 0.2 ng
19 thiamethoxam/bee). There was no evidence that injection treatment altered sucrose consumption
20 (all experiments: ANOVA $P > 0.05$).

21 **4. DISCUSSION**

1 Four antimicrobial effector genes showed a clear upregulation in response to the artificial
2 immune challenge. The response to immune challenge differed between the two defensin genes
3 tested (defensin-1 and defensin-2), which is consistent with previous studies (Evans 2006) and
4 known differences in the regulation of the two genes (Klaudiny et al. 2005). The lack of a
5 detectable response by lysozyme-1 is consistent with most of the previous studies of bacterial
6 infection in honey bees (e.g. Evans 2006, Yang and Cox-Foster 2005). This may reflect the
7 proposition that lysozymes act by hydrolysing the peptidoglycan cell wall (Gillespie et al. 1997)
8 and so are more effective against Gram-positive bacteria, which have a thicker peptidoglycan
9 layer. Therefore, it is perhaps not surprising that lysozyme-1 was not found to be upregulated in
10 response to the LPS molecules from Gram-negative *E.coli* in the present study.

11 The transcriptional changes in AMP genes in response to immune challenge that occurred in our
12 study probably have functional significance because they were accompanied by increases in
13 antimicrobial activity at the protein/enzyme level. Wounding by injection alone induced an
14 antimicrobial response, albeit to a lesser extent than injection with bacterial LPS, which is
15 consistent with previous studies (Evans et al. 2006, Laughton et al. 2011, Yang and Cox-Foster
16 2005). The wound-response to injection that we observed may be similar to the response to other
17 natural wounding events, such as puncturing by *Varroa* mites (Kanbar and Engels 2003) and
18 parasitic flies (Core et al. 2012). It is likely that an increased response in transcription of AMP-
19 related genes following wounding is adaptive by allowing the honey bee to pre-emptively induce
20 its immune system before microbial infection, because most natural wounds will inevitably be
21 non-sterile (Erler et al. 2011, Kanbar and Engels 2003).

22 The effects of neonicotinoid exposure on transcriptional responses in the antimicrobial
23 component of honey bee immunity were weak and inconsistent. Where transcriptional changes

1 were observed, they differed between the two neonicotinoid compounds. Generally, expression
2 was altered in a greater number of the genes tested following exposure to thiamethoxam than to
3 the much higher exposure to imidacloprid, but even in the case of thiamethoxam the results were
4 inconsistent because effects differed between the short- and long- time course experiments, even
5 at equivalent time points.

6 Neonicotinoid exposure did not affect the physiological activity of the antimicrobial response in
7 our study as measured by a lytic clearance assay, even when transcriptional changes in AMP
8 gene expression were observed. Taken together, our findings therefore suggest that the
9 transcriptional changes in AMP genes due to neonicotinoid exposure that we observed did not
10 indicate a detrimental impact on bee health through suppressed immunocompetence, contrary to
11 what has been proposed by others (e.g. Di Prisco et al. 2013). We tentatively speculate that
12 differential gene expression may fail to cause a correspondingly altered physiological response.
13 If the insecticide evokes various positive and negative changes in the expression of antimicrobial
14 genes, overall, the system may be virtually left in balance. For example, we observed that
15 thiamethoxam both suppressed hymenoptaecin expression and increased apidaecin expression.

16 Our findings have implications for the future development of molecular biomarkers of bee health
17 under pesticide and pathogen exposures. There has been recent interest in identifying suitable
18 molecular biomarkers for pesticide risk assessment on bees (EFSA 2012). However, our findings
19 do not yet validate the use of the immune-related molecular biomarkers in risk assessment,
20 principally because we found that enzymatic/protein-level components of honey bee
21 antimicrobial activity were unaffected by neonicotinoid exposure despite the occurrence of some
22 temporally coincident, pesticide-induced transcriptional changes in AMP genes. In summary, if
23 the loci that we studied were to be used as molecular biomarkers, our findings imply that they

1 would be overly sensitive indicators of alterations in the physiological capacities of honey bees
2 to mount an immune response. However, it is unknown whether our findings for neonicotinoids
3 are typical for other classes of chemical compounds.

4 We recognise that our findings must be considered with some caveats. First, we conducted a
5 series of separate experiments on individual honey bee colonies and this may have some bearing
6 on our conclusions. Specifically, while our findings certainly suggest the potential for differences
7 in the response of different immune endpoints to pesticide exposure, some of these differences
8 could result also from between-colony variation in pesticide sensitivity. In the future, further
9 work could compare transcriptional and physiological responses of honey bees both within a
10 single colony as well as among a number of colonies, and also within and between seasons.
11 Second, further research is needed to establish whether the resilience of the response to
12 simulated immune-stimulus in pesticide-exposed honey bees also arises when they are
13 challenged by their natural pathogens. We tentatively predict that our findings will generalise to
14 natural pathogens because of the commonality of responses by several AMP genes under
15 infection with a broad range of challenges, including honey bee bacterial, fungal and
16 microsporidian pathogens (Antunez et al. 2009, Evans 2006). In the future, however, only
17 investigations using natural pathogens can truly assess environmentally relevant impacts of
18 pesticides on bee health. Finally, our laboratory findings are yet to be generalised to honey bee
19 colonies under realistic in-hive conditions. Although we detected no functionally significant
20 impacts on honey bee immunocompetence in laboratory exposures that probably exceed many
21 environmentally relevant neonicotinoid exposures, we are also tentative in generalising our
22 findings to bees under field-relevant conditions for three reasons. First, our experimental
23 exposures were conducted for periods of up to 11 days, whereas realistic in-hive exposures may

1 be for longer periods. Second, our laboratory setup did not provide access to a pollen supply and
2 pollen nutrition has been shown to affect immunocompetence (Alaux et al. 2010b). Third, we
3 tested only a subset of endpoints and there are many other functionally relevant genes and
4 enzymes belonging to various pathways in the honey bee immune system.

5 **5. CONCLUSIONS**

6 In summary, our experiments showed an overall clear temporal pattern of AMP gene expression
7 and physiological activity in response to a bacterial-like infection. Our principal finding is that
8 the transcriptional changes in AMP genes following neonicotinoid exposure did not correspond
9 with immune suppression at the physiological level. If this finding turns out to be general, it
10 suggests that honey bee immunity may be more resilient to neonicotinoid exposure than
11 previously thought based on molecular studies only, but this will need further investigation and,
12 particularly, using honey bees maintained under environmentally realistic conditions. Our
13 findings begin to enable regulators to better evaluate the potential of gene expression as a
14 biomarker for bee health. For those genes studied here, bioassays based on gene expression are
15 not yet reliable indicators of pesticide effects on honey bee immune functioning at a
16 physiological level.

17 **ACKNOWLEDGEMENTS**

18 E.J.C was funded by a joint University of Exeter-Fera studentship. We thank Ben Jones and Joy
19 Kaye for assistance in setting up enzymatic and molecular assays respectively. We gratefully
20 acknowledge the laboratory support from numerous staff and students in the NBU and CCSS at
21 Fera, York.

1 **REFERENCES**

- 2 Alaux, C., Brunet, J.-L., Dussaubat, C., Mondet, F., Tchamitchan, S., Cousin, M., Brillard, J.,
3 Baldy, A., Belzunces, L. P., Le Conte, Y. (2010a) Interactions between *Nosema* microspores and
4 a neonicotinoid weaken honeybees (*Apis mellifera*). Environ. Microbiol. **12**, 774-782
- 5 Alaux, C., Ducloz, F., Crauser, D., Le Conte, Y. (2010b) Diet effects on honeybee
6 immunocompetence. Biol. Lett. **6**, 562-565
- 7 Alaux, C., Kemper, N., Kretzschmar, A., Le Conte, Y. (2012) Brain, physiological and
8 behavioral modulation induced by immune stimulation in honeybees (*Apis mellifera*): A
9 potential mediator of social immunity? Brain, Behav. and Immun. **26**, 1057-1060
- 10 Antunez, K., Martin-Hernandez, R., Prieto, L., Meana, A., Zunino, P., Higes, M. (2009) Immune
11 suppression in the honey bee (*Apis mellifera*) following infection by *Nosema ceranae*
12 (Microsporidia). Environ. Microbiol. **11**, 2284-2290
- 13 Brandt, A., Gorenflo, A., Siede, R., Meixner, M., Büchler, R. (2016) The neonicotinoids
14 thiacloprid, imidacloprid, and clothianidin affect the immunocompetence of honey bees (*Apis*
15 *mellifera* L.). J. Insect Physiol. **86**, 40-47
- 16 Collison, E., Hird, H., Cresswell, J., Tyler, C. (2016) Interactive effects of pesticide exposure
17 and pathogen infection on bee health – a critical analysis. Biol. Rev. **91**, 1006-1019
- 18 Core, A., Runckel, C., Ivers, J., Quock, C., Siapno, T., Denault, S., Brown, B., Derisi, J., Smith,
19 C. D., Hafernik, J. (2012) A new threat to honey bees, the parasitic phorid fly *Apocephalus*
20 *borealis*. PLoS ONE **7**(1), e29639

1 Cotter, S. C., Myatt, J. P., Benskin, C. M. H., Wilson, K (2008) Selection for cuticular melanism
2 reveals immune function and life-history trade-offs in *Spodoptera littoralis*. J. Evolut. Biol. **21**,
3 1744-1754

4 Derecka, K., Blythe, M. J., Malla, S., Genereux, D. P., Guffanti, A. et al. (2013) Transient
5 exposure to low levels of insecticide affects metabolic networks of honeybee larvae. PLoS ONE
6 **8**(7), e68191

7 Di Prisco, G., Cavaliere, V., Annoscia, D., Varricchio, P., Caprio, E., Nazzi, F., Gargiulo, G.,
8 Pennacchio, F. (2013) Neonicotinoid clothianidin adversely affects insect immunity and
9 promotes replication of a viral pathogen in honey bees. Proc. Natl. Acad. Sci. USA **110**, 18466-
10 71

11 EFSA (2012) European Food Safety Authority Panel on Plant Protection Products and their
12 Residues: Scientific Opinion on the science behind the development of a risk assessment of Plant
13 Protection Products on bees (*Apis mellifera*, *Bombus* spp. and solitary bees). EFSA Journal **10**(5)
14 2668

15 Erler, S., Popp, M., Lattorff, H. M. G. (2011). Dynamics of immune system gene expression
16 upon bacterial challenge and wounding in a social insect (*Bombus terrestris*). PLoS ONE **6**(3),
17 e18126

18 Evans, J. D. (2006) Beepath: An ordered quantitative-PCR array for exploring honey bee
19 immunity and disease. J. Invertebr. Pathol. **93**, 135-139

- 1 Evans, J. D., Aronstein, K., Chen, Y. P., Hetru, C., Imler, J. L., Jiang, H., Kanost, M.,
2 Thompson, G. J., Zou, Z., Hultmark, D. (2006) Immune pathways and defence mechanisms in
3 honey bees *Apis mellifera*. *Insect Mol. Biol.* **15**, 645-656
- 4 Gättschenberger, H., Azzami, K., Tautz, J., Beier, H. (2013) Antibacterial immune competence of
5 honey bees (*Apis mellifera*) is adapted to different life stages and environmental risks. *PLoS*
6 *ONE* **8**(6), e66415
- 7 Gillespie, J. P., Kanost, M. R. & Trenczek, T. (1997) Biological mediators of insect immunity.
8 *Annu. Rev. Entomol.* **42**, 611-643
- 9 Gregorc, A., Evans, J. D., Scharf, M., Ellis, J. D. (2012) Gene expression in honey bee (*Apis*
10 *mellifera*) larvae exposed to pesticides and *Varroa* mites (*Varroa destructor*). *J. Insect Physiol.*
11 **58**, 1042-1049
- 12 Kanbar, G., Engels, W. (2003) Ultrastructure and bacterial infection of wounds in honey bee
13 (*Apis mellifera*) pupae punctured by *Varroa* mites. *Parasitol Res.* **90**, 349-354
- 14 Klaudiny, J., Albert, S., Bachanova, K., Kopernicky, J., Simuth, J. (2005) Two structurally
15 different defensin genes, one of them encoding a novel defensin isoform, are expressed in
16 honeybee *Apis mellifera*. *Insect Biochem. Mol. Biol.* **35**, 11-22
- 17 Köhler, A., Pirk, C. W. W., Nicolson, S. W. (2012) Simultaneous stressors: Interactive effects of
18 an immune challenge and dietary toxin can be detrimental to honeybees. *J. Insect Physiol.* **58**,
19 918-923
- 20 Korner, P., Schmid-Hempel, P. (2004) In vivo dynamics of an immune response in the bumble
21 bee *Bombus terrestris*. *J. Invertebr. Pathol.* **87**, 59-66

- 1 Laughton, A. M., Boots, M., Siva-Jothy, M. T. (2011) The ontogeny of immunity in the honey
2 bee, *Apis mellifera* L. following an immune challenge. *J. Insect Physiol.* **57**, 1023-1032
- 3 Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W. E. (2010)
4 Global pollinator declines: trends, impacts and drivers. *Trends Ecol. Evol.* **25**, 345-353
- 5 Riddell, C. E., Sumner, S., Adams, S., Mallon, E. B. (2011) Pathways to immunity: temporal
6 dynamics of the bumblebee (*Bombus terrestris*) immune response against a trypanosomal gut
7 parasite. *Insect Mol. Biol.* **20**, 529-540
- 8 Stoner, K. A., Eitzer, B. D. (2012) Movement of soil-applied imidacloprid and thiamethoxam
9 into nectar and pollen of squash (*Cucurbita pepo*). *PLoS ONE* **7**(6), e39114
- 10 Yang, X. L., Cox-Foster, D. L. (2005) Impact of an ectoparasite on the immunity and pathology
11 of an invertebrate: Evidence for host immunosuppression and viral
12

1 **FIGURE CAPTIONS**

2 **Fig. 1** Gene expression of the AMP gene, abaecin, in response to artificial immune challenge
3 over time in control-fed (black shapes) and neonicotinoid-exposed (white shapes) bees. Top
4 plots: Results for exposure to 125 µg/L imidacloprid [Experiments A (left) and D (right)].
5 Bottom plots: Results for exposure to 12 µg/L thiamethoxam [Experiments A (left) and E
6 (right)]. Plots on the left hand side show responses for a period of 2-48 h post immune challenge
7 (PIC) and plots on the right hand side for a period of 1-7 d PIC. In all plots, shapes indicate
8 sample means and error bars depict 1 SE. Only upper error bars are shown to simplify the figures
9

10 **Fig. 2** Physiological antimicrobial activity to artificial immune challenge over time in control-fed
11 (black shapes) and neonicotinoid-exposed (white shapes) bees. Top plots: Results for exposure to
12 125 µg/L imidacloprid [Experiments B (left) and D (right)]. Bottom plots: Results for exposure
13 to 12 µg/L thiamethoxam [Experiments C (left) and E (right)]. Plots on the left hand side show
14 responses for a period of 2-48 h post immune challenge (PIC) and plots on the right hand side for
15 a period of 1-7 d PIC. Note, the y-axis scales differ between plots. In all plots, shapes indicate
16 sample means and error bars depict 1 SE. Only upper error bars are shown to simplify the figures
17

1 **TABLES**

2 **Table I** Overview of the test substances, sampling time course and endpoints measured in each
 3 of five experiments. Each experiment was performed with newly emerged honey bees from a
 4 single colony. A different colony was used for each experiment. See supplementary material for
 5 an overall setup of treatment and sampling combinations.

6

Experimental details		Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Pesticides tested in each experiment ¹	Control vs 125 µg/L IMI	✓	✓		✓	
	Control vs 12 µg/L TMX	✓		✓		✓
Samples taken across either 'short' of 'long' time course in each experiment	Short time course (2-48 h)	✓	✓	✓		
	Long time course (24-168 h)				✓	✓
Endpoints measured in each experiment ²	Gene expression (qPCR)	✓			✓	✓
	AMP enzymatic activity		✓	✓	✓	✓
Total combinations tested (total no. of cages in parentheses)³		54 (162)	24 (72)	24 (72)	60 (180)	60 (180)

7 IMI = imidacloprid; TMX = thiamethoxam

8 ¹ Where both compounds were tested in a single experiment, each compound was tested independently. i.e. cages of
 9 10 bees were exposed to either IMI or TMX, but never to both. Where boxes are left blank, the pesticide of concern
 10 was not tested in the given experiment.

11 ² Where both gene expression and enzymatic activity were measured in a single experiment, each endpoint was
 12 tested independently. i.e. individual bees were used in samples for either gene expression or enzymatic activity, but
 13 never for both. Where boxes are left blank, the endpoint of concern was not tested in the given experiment.

14 ³ Combinations of pesticide x immune challenge x sampling time point x measurement type. Please refer to
 15 supplementary material for overview of all combinations. Note, the total number of combinations across all
 16 experiments is greater than 180 because control groups were included in all experiments. In all experiments, 3 cages
 17 (replicates) of 10 bees were tested per combination.

1 **Table II (next page)** ANOVA results for all five experiments. Data analysis was only
2 conducted between samples within a single experiment, but presented below to show all
3 comparisons/endpoints tested across the five experiments. Variation among treatments
4 was analysed by factorial ANOVA with injection (immune challenge) treatment,
5 pesticide treatment and time post immune challenge as fixed effects. ‘Injection’ refers to
6 comparison between the ‘Ringer’s’ and ‘LPS’ injection groups; this injection
7 comparison was seen of most biological relevance as it reflected responses only to the
8 bacterial molecules (albeit artificial), but not to the injection procedure itself. ‘Pesticide’
9 refers to comparison between control-fed and pesticide-fed bees (either imidacloprid or
10 thiamethoxam, depending on the experiment).

11

		Abaccin		Apidaecin		Hymenoptaecin		Defensin1		Defensin2		Lysozyme1		AMP enzymatic activity			
		Experiment A ¹												Experiment B ²			
Short time course (0 – 48 h)	IMIDACLOPRID	df	F	P	F	P	F	P	F	P	F	P	F	P	df	F	P
	Injection	1	106	<0.001	27.0	<0.001	176	<0.001	30.3	<0.001	2.42	0.126	2.68	0.107	1	18.2	<0.001
	Pesticide	1	1.21	0.278	0.617	0.436	0.051	0.823	4.62	0.036	0.497	0.484	1.04	0.313	1	2.93	0.096
	Time	5	141	<0.001	34.3	<0.001	153	<0.001	28.6	<0.001	1.09	0.377	1.98	0.097	3	160	<0.001
	Injection*Pesticide	1	3.39	0.071	2.79	0.101	5.38	0.024	0.532	0.469	0.187	0.668	0.176	0.676	1	4.12	0.050
	Pesticide*Time	5	0.319	0.899	0.068	0.997	1.41	0.235	0.868	0.509	1.28	0.287	0.876	0.504	3	1.49	0.234
	Injection*Time	5	13.1	<0.001	3.73	0.006	20.3	<0.001	2.39	0.050	0.220	0.952	0.147	0.980	3	6.72	0.001
	Residuals	53													35		
		Experiment A ¹												Experiment C ²			
Short time course (0 – 48 h)	THIAMETHOXAM	df	F	P	F	P	F	P	F	P	F	P	F	P	df	F	P
	Injection	1	96.8	<0.001	31.3	<0.001	93.3	<0.001	20.6	<0.001	0.489	0.487	0.368	0.547	1	27.8	<0.001
	Pesticide	1	11.5	0.001	21.8	<0.001	47.8	<0.001	3.85	0.055	1.67	0.202	8.60	0.005	1	0.013	0.908
	Time	5	81.6	<0.001	35.4	<0.001	87.0	<0.001	27.3	<0.001	2.66	0.033	5.45	<0.001	3	88.6	<0.001
	Injection*Pesticide	1	10.7	0.002	0.615	0.436	3.31	0.075	0.012	0.915	4.70	0.035	1.62	0.209	1	0.952	0.336
	Pesticide*Time	5	1.87	0.115	3.88	0.005	14.3	<0.001	1.28	0.287	2.24	0.064	6.07	<0.001	3	0.811	0.496
	Injection*Time	5	7.45	<0.001	3.12	0.015	16.1	<0.001	3.13	0.015	2.23	0.065	1.88	0.113	3	9.15	<0.001
	Residuals	52													35		
		Experiment D ^{2,3}															
Long time course (0 – 168 h)	IMIDACLOPRID	df	F	P	F	P	F	P	F	P	F	P	F	P	df	F	P
	Injection	1	25.4	<0.001	48.3	<0.001	14.6	<0.001	-	-	-	-	-	-	1	119	<0.001
	Pesticide	1	0.022	0.883	2.75	0.106	0.074	0.787	-	-	-	-	-	-	1	0.134	0.717
	Time	3	16.0	<0.001	13.2	<0.001	9.41	<0.001	-	-	-	-	-	-	3	42.1	<0.001
	Injection*Pesticide	1	3.38	0.075	0.879	0.355	0.629	0.433	-	-	-	-	-	-	1	0.105	0.748
	Pesticide*Time	3	1.18	0.334	0.279	0.840	1.23	0.315	-	-	-	-	-	-	3	1.36	0.272
	Injection*Time	3	0.801	0.502	0.879	0.485	4.90	0.006	-	-	-	-	-	-	3	6.99	<0.001
	Residuals	34													34		
		Experiment E ^{2,3}															
Long time course (0 – 168 h)	THIAMETHOXAM	df	F	P	F	P	F	P	F	P	F	P	F	P	df	F	P
	Injection	1	32.9	<0.001	32.2	<0.001	37.0	<0.001	-	-	-	-	-	-	1	44.3	<0.001
	Pesticide	1	0.989	0.327	0.359	0.554	0.272	0.606	-	-	-	-	-	-	1	0.039	0.845
	Time	3	13.7	<0.001	15.8	<0.001	15.1	<0.001	-	-	-	-	-	-	3	35.0	<0.001
	Injection*Pesticide	1	0.25	0.624	1.57	0.219	0.047	0.830	-	-	-	-	-	-	1	0.088	0.769

	Pesticide*Time	3	0.799	0.503	0.199	0.896	1.81	0.164	-	-	-	-	-	-	3	0.655	0.586
	Injection*Time	3	3.06	0.042	4.29	0.012	2.36	0.090	-	-	-	-	-	-	3	3.39	0.029
	Residuals	33													33		

1 ¹ In Experiment A, where imidacloprid and thiamethoxam treatments were both included within the single experiment, the imidacloprid and thiamethoxam datasets
2 were analysed separately as we were only interested in the differences between each pesticide and the control-fed bees. Since the control dataset was therefore used in
3 both analyses, in Experiment A a significant effect was defined by $P \leq 0.025$ (in bold), accounting for a Bonferroni correction.

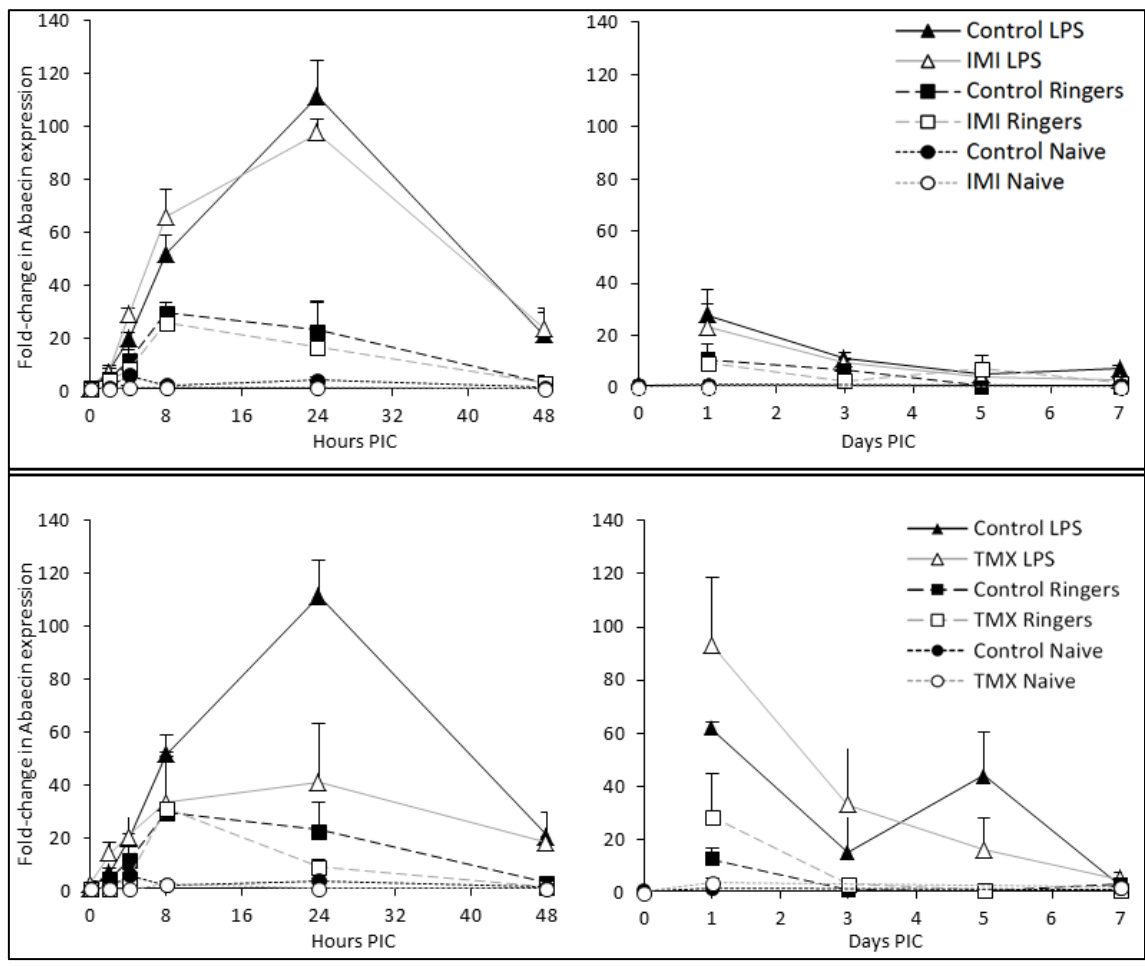
4 ² Significant effect defined by $P \leq 0.05$ (in bold).

5 ³ Expression of the genes Defensin1, Defensin2 and Lysozyme1 was not measured in the long time course experiments (experiments D and E).

1 FIGURES

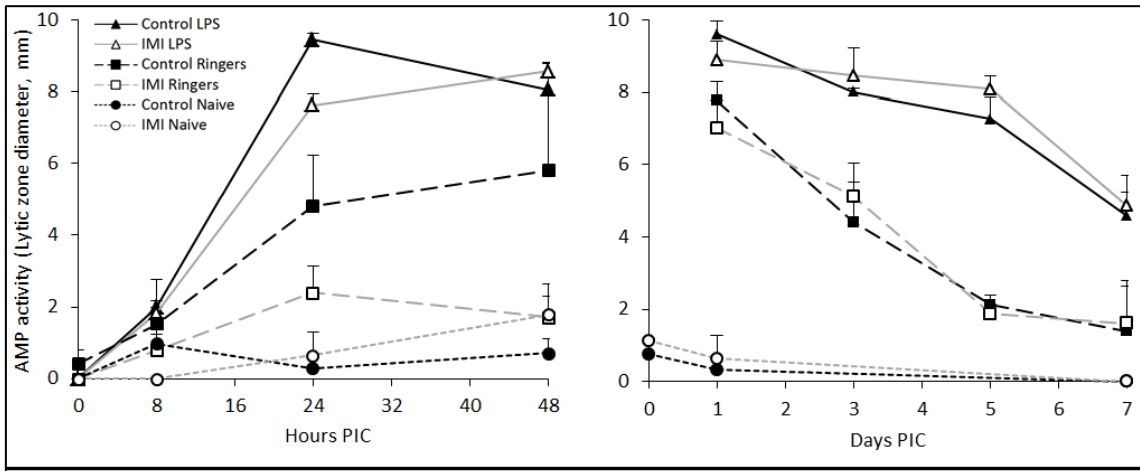
2

3 Fig. 1



4
5

1 Fig. 2



2

