Odorant receptor orthologues in conifer-feeding beetles display conserved responses to ecologically relevant odors

Running title: Conserved responses in odorant receptors

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Abstract

Insects are able to detect a plethora of olfactory cues using a divergent family of odorant receptors (ORs). Despite the divergent nature of this family, related species frequently express several evolutionarily conserved OR orthologues. In the largest order of insects, Coleoptera, it remains unknown whether OR orthologues have conserved or divergent functions in different species. Using HEK293 cells, we addressed this question through functional characterization of two groups of OR orthologues in three species of the Curculionidae (weevil) family, the conifer-feeding bark beetles *Ips typographus* L. ('Ityp') and *Dendroctonus ponderosae* Hopkins ('Dpon') (Scolytinae), and the pine weevil *Hylobius abietis* L. ('Habi'; Molytinae). The ORs of *H. abietis* were annotated from antennal transcriptomes. Results show highly conserved response specificities, with one group of orthologues (HabiOR3/DponOR8/ItypOR6) responding exclusively to 2-phenylethanol (2-PE), and the other group (HabiOR4/DponOR9/ItypOR5) responding to angiosperm green leaf volatiles (GLVs). Both groups of orthologues belong to the coleopteran OR subfamily 2B, and share a common ancestor with OR5 in the cerambycid *Megacyllene caryae*, also tuned to 2-PE, suggesting a shared evolutionary history of 2-PE receptors across two beetle superfamilies. The detected compounds are ecologically relevant for conifer-feeding curculionids, and are probably linked to fitness, with GLVs being used to avoid angiosperm non-host plants, and 2-PE being important for intraspecific communication and/or playing a putative role in beetle-microbe symbioses. To our knowledge, this study is the first to reveal evolutionary conservation of OR functions across several beetle species and hence sheds new light on the functional evolution of insect ORs.

Keywords

Functional characterization; de-orphanization; HEK293 cells; evolutionary conservation; Coleoptera; Curculionidae.

Introduction

Insects are able to detect thousands of different chemical cues that convey important information about the environment, including plant volatiles, microbial odors, and pheromones (Dahanukar et al. 2005; Hansson & Stensmyr 2011; Kandasamy et al. 2019; Stensmyr et al. 2012). This sophisticated discernment of odors is possible via large suites of odorant receptors (ORs), which bind and detect odor molecules in peripheral olfactory sensory neurons (OSNs), triggering neuronal signals to be processed by the central nervous system (Brand et al. 2018; Clyne et al. 1999; Sato et al. 2008; Vosshall et al. 1999; Wicher et al. 2008). These seven-transmembrane proteins form heteromeric complexes with a highly conserved co-receptor (Orco), which is necessary for odor responses in most insects by contributing to the formation of a ligand-gated ion channel (Butterwick et al. 2018; Larsson et al. 2004).

The OR gene family evolves according to a birth-and-death model, in which duplication events represent the birth of genes, and deletion or pseudogenization their death (Nei et al. 2008). Accordingly, OR genes are often found in tandem arrays on insect chromosomes, with significant variation in the size of OR repertoires between species (Andersson et al. 2015; Benton 2015; Brand & Ramírez 2017). Frequently, the majority of ORs in a given species are present within species- or taxon-specific phylogenetic OR-lineage radiations (Mitchell et al. 2020). Within such radiations, novel olfactory functions may evolve due to relaxed constraints or positive selection post gene duplication, provided the duplicated gene is retained and expressed (Andersson et al. 2015; Hou et al. 2021). Despite the general divergent nature of this receptor family, certain ORs are conserved across species, with simple (1:1) orthologous OR-pairs typically being present among related species. However, such clear orthology is usually rare or absent when comparing more distantly related insect species from

different families, which has been shown in e.g., beetles (Coleoptera) (Mitchell & Andersson 2020; Mitchell et al. 2020). Whether OR orthologues share the same or similar olfactory functions, or if functions have diverged in different species, has been studied primarily in Lepidoptera and Diptera (e.g., Bohbot et al. 2011; M. Guo et al. 2021). Such studies are important for advancing our understanding of the functional evolution of the insect OR family, as they may inform shared ecological relevance of certain compounds in different species, hence shared selection pressures acting on the olfactory sense of insects. For example, the host- and oviposition cues 1-octen-3-ol, indole and skatole, respectively, are detected by orthologous groups of ORs across several mosquito species (Dekel et al. 2016; Ruel et al. 2019). In moths, some olfactory functions are widely conserved among OR orthologues, including both the detection of specific plant odors and sex pheromone compounds, whereas other orthologues are functionally different (Gonzalez et al. 2015; H. Guo et al. 2021; M. Guo et al. 2021).

In contrast, nothing is known about the functions of OR orthologues in beetles, which is not surprising given the very few ORs that have been functionally characterized in this large order. The response profiles of seven ORs have been characterized from the Eurasian spruce bark beetle *Ips typographus* L. ('Ityp'; Curculionidae) (Hou et al. 2021; Roberts et al. 2021a; Yuvaraj et al. 2021), two ORs from the red palm weevil *Rhynchophorus ferrugineus* Olivier (Curculionidae) (Antony et al. 2021; Ji et al. 2021), one OR from the dark black chafer *Holotrichia parallela* Motschulsky (Scarabaeidae) (Wang et al. 2020), one OR from the Adonis ladybird *Hippodamia variegata* Goeze (Coccinellidae) (Xie et al. 2022) and three ORs from the hickory borer *Megacyllene caryae* Gahan ('Mcar'; Cerambycidae) (Mitchell et al. 2012). Among the characterized ORs of this cerambycid, McarOR5 responded strongly to the male-produced pheromone component 2-phenylethanol (2-PE) (Mitchell et al. 2012).

99 McarOR5 belongs to the beetle OR subfamily named Group 2B, which contains conserved
100 OR lineages with receptors from several beetle families, including the large family of true
101 weevils, Curculionidae (Mitchell et al. 2020). This beetle family harbors the damaging
102 conifer-feeding bark beetles of the Scolytinae subfamily and many other weevils that are pests
103 of agriculture and forestry, such as the pine weevil *Hylobius abietis* L. ('Habi'; Molytinae)
104 (Shin et al. 2018). The 2-PE is ecologically relevant for several conifer-feeding beetles. For
105 instance, it is part of the attractive odor bouquets released by the fungal symbionts of *I.*
106 *typographus* (Kandasamy et al. 2019) and the compound has also been identified from the
107 hindgut of male beetles, where it may be produced by yeasts (Leufvén et al. 1984), in highest
108 amounts before the acceptance of females (Birgersson et al. 1984). The compound is the
109 primary odorant for one of the characterized OSN classes of *I. typographus* (Kandasamy et
110 al., 2019), suggesting that this species is likely to have an OR tuned to this compound. Also
111 *Dendroctonus* bark beetles produce this compound (Sullivan 2005), including the mountain
112 pine beetle *D. ponderosae* Hopkins ('Dpon'; Curculionidae), in which 2-PE reduces the
113 attraction to the aggregation pheromone (Pureswaran et al. 2000). In the pine weevil *H.*
114 *abietis*, 2-PE operates as a strong anti-feedant present in deterrent non-host plants (Eriksson et
115 al. 2008). Interestingly, 2-PE is also produced by gut bacteria of *H. abietis*, and the behavior
116 of this species, to cover their laid eggs with feces and frass containing deterrent compounds,
117 may protect the eggs from being eaten by conspecifics (Axelsson et al. 2017; Borg-Karlson et
118 al. 2006).
119
120 Due to the widespread use of 2-PE in the ecologies of conifer-feeding curculionids, we
121 hypothesized that the compound may be detected by evolutionarily and functionally
122 conserved ORs and that these receptors may be related to McarOR5. To test this hypothesis,
123 we used HEK293 cells to functionally characterize two clades with simple OR orthologues

124 from three curculionids (*I. typographus*, *D. ponderosae*, and *H. abietis*), i.e., the orthologues
125 in OR Group 2B that are positioned closest to McarOR5 in the OR phylogeny. The OR
126 repertoires of the two bark beetles have been previously reported (Andersson et al. 2013;
127 Andersson et al. 2019; Yuvaraj et al. 2021); however, to obtain the OR sequences from *H.*
128 *abietis* we sequenced, analyzed, and annotated male and female antennal transcriptomes. Our
129 results show that 2-PE is indeed detected by functionally conserved and highly specific OR
130 orthologues in all three curculionids. These ORs share a common ancestor with McarOR5
131 suggesting functional conservation also across two beetle superfamilies (Curculionoidea and
132 Chrysomeloidea). Additionally, green leaf volatile (GLV) alcohols, abundant in non-host
133 angiosperm plants and generally avoided by conifer-feeding beetles (Zhang & Schlyter 2004),
134 were detected by the second assayed clade of curculionid ORs. These receptors share
135 evolutionary history with the ORs detecting 2-PE. Altogether, our findings suggest strong
136 functional conservation in ORs detecting ecologically important odors, and thereby expand
137 our knowledge of the functional evolution of the OR family in the largest order of insects.
138

139 Materials and Methods

140 *Sequencing, assembly, annotation, and analyses of the* **Hylobius abietis** *antennal*
141 *transcriptome*

142 Wild beetles were collected by hand at Balungstrand's sawmill in Enviken, close to Falun in
143 mid-Sweden, and kindly provided by Prof. Göran Nordlander (Swedish University of
144 Agricultural Sciences, Uppsala, Sweden). The antennae from 20 males and 20 females were
145 excised and collected separately in tubes kept on dry ice and then stored at −80 °C. The
146 antennae were homogenized using Tissue-tearor model 98370-365 (Bartlesville, OK, USA),
147 and total RNA was isolated using the RNeasy Minikit (Qiagen, Hilden, Germany).
148 Extractions yielded 4.8 µg and 3.1 µg of high-quality total RNA from male and female

149 antennal samples, respectively. These RNA samples were used for both transcriptome
150 sequencing and molecular cloning.
151
152 The RNA samples were DNase-treated and then underwent poly-A enrichment and library
153 construction using a TruSeq v2 Library Preparation Kit (Illumina, San Diego, CA, USA),
154 followed by 150 bp paired-end sequencing on an Illumina HiSeq 3000 platform at the Max
155 Planck-Genome center (Cologne, Germany). The sequencing produced 36,455,021 and
156 35,770,733 paired-end reads from the male and female samples, respectively. Adaptor
157 sequences and low-quality reads were removed using Trimmomatic (v 0.36) (Bolger et al.
158 2014) with a custom screening database, before performing *de novo* assemblies with Trinity
159 version 2.4.0 (Grabherr et al. 2011). Reads from males and females were assembled
160 separately, and also combined. Contigs from the Trinity output were clustered to reduce the
161 number of redundant transcripts using CD-HIT-EST (v 4.6.8) (Li & Godzik 2006) with a
162 sequence identity threshold of 0.98. Primarily, the sex-combined non-redundant assembly was
163 used for downstream annotation of OR-encoding transcripts, and was comprised of 46,669
164 predicted protein-coding 'genes' with their respective isoforms and together with other non-
165 coding genes totaled 199,035 transcripts. The average transcript length was 824 bp with an
166 N50 of 1,570 bp. The completeness of the sex-combined assembly was firstly assessed using
167 the Benchmarking Universal Single-Copy Orthologs (BUSCO v5.2.2;
168 https://busco.ezlab.org/) tool performed against the Insecta odb10 dataset, including 1,367
169 reference genes (Manni et al. 2021). This analysis revealed 96.6% complete (C) BUSCOs, of
170 which 59.8% were present as single copy genes (S) and 40.2% as duplicated genes (D). Only
171 30 (2.3%) BUSCOs were missing (M) from the assembly and 17 (1.3%) BUSCOs were
172 fragmented (F), indicating the majority of transcripts were represented and were full length.
173 Mapping of the clean reads to the non-redundant assembly resulted in an overall alignment

174 rate of 94.06%, further demonstrating a high level of completeness for this assembly. The
175 RNAseq reads have been deposited in the SRA database at NCBI under the BioProject
176 accession number PRJNA783427.
177
178 *H. abietis* OR genes were annotated through exhaustive tBLASTn searches against the
179 assemblies at an *e*-value cut-off at 1.0. The OR query sequences were obtained from *I.*
180 *typographus* (Andersson et al. 2013; Yuvaraj et al. 2021), *D. ponderosae* (Andersson et al.
181 2013; Andersson et al. 2019), *Anoplophora glabripennis* (McKenna et al. 2016), *M. caryae*
182 (Mitchell et al. 2012), and *Leptinotarsa decemlineata* (Schoville et al. 2018). All annotated
183 HabiOR sequences were included in additional tBLASTn searches against the *H. abietis*
184 assemblies until all novel OR hits were exhausted. Except for the HabiOrco gene which was
185 only assembled to full length in the male-specific assembly, all OR genes were annotated
186 from the sex-combined assembly, and no OR genes were uniquely found or assembled to
187 higher completeness in the two sex-specific assemblies. A few partial OR genes could be
188 extended by joining overlapping transcripts with identical sequences. The names of these
189 genes were given a 'JOI' suffix according to established nomenclature (Andersson et al. 2019,
190 and references therein). Likewise, OR genes missing the N-terminus or C-terminus were
191 given the suffixes 'NTE' and 'CTE', respectively, to their names. Single letter abbreviations
192 were used in combinations (i.e., J, N, C) for genes with multiple suffixes. Transcripts
193 encoding partial OR sequences below 170 amino acids and those that that did not overlap
194 with other OR sequences in multiple sequence alignments were discarded as they may not
195 represent unique genes. Likewise, for ORs sharing >96% amino acid identity, only one
196 transcript was kept in the dataset to exclude potential assembly isoforms or allelic variants.
197 The identified HabiOR genes were given names from HabiOR1 to HabiOR78 following their

198 groupings in the OR phylogeny (Fig. 1), with consecutive numbering within the major
199 coleopteran OR clades (Mitchell et al. 2020).
200
201 To analyze the expression levels of OR genes in male and female antennae, clean reads were
202 mapped to the ORFs of annotated HabiOR genes using the align_and_estimate_abundance.pl
203 script from the Trinity v2.4.0 software package (Haas et al. 2013) with default parameters
204 except for --est_method RSEM--aln_method bowtie2 --trinity_mode. The rationale for
205 mapping to the ORFs of OR genes, and not to all transcripts in the assembly, was because
206 some OR transcripts contained misassembled fragments in non-coding regions, which could
207 bias the estimated expression level of the OR gene.
208
209 The HabiOR amino acid sequences were aligned with the OR sequences from *D. ponderosae*
210 (Andersson et al. 2019), *I. typographus* (Yuvaraj et al. 2021), and *M. caryae* (Mitchell et al.
211 2012) using MAFFT v7.450 (Katoh et al. 2002; Katoh & Standley 2013), implemented in
212 Geneious Prime v.2020.0.5 (Biomatters Ltd. Auckland, New Zealand). The alignment of a
213 few partial OR sequences were corrected manually. Three miss-aligned partial McarOR
214 sequences (McarORs 41PAR, 50PAR, and 53PAR) were excluded from analysis since their
215 alignments could not be corrected with confidence. Uninformative regions were excised using
216 trimAl v.1.2 (Capella-Gutiérrez et al. 2009) with the following settings: similarity threshold 0,
217 gap threshold 0.7, and minimum 25% conserved positions. The trimmed alignment was used
218 to construct a phylogenetic tree of ORs using FastTree v.2.1.11 at default settings (Price et al.
219 2010). Local node support values were calculated using the Shimodaira-Hasegawa (SH) test
220 implemented within FastTree. The tree was rooted with the Orco lineage, and color coded in
221 FigTree v.1.4.3 (Rambaut 2014). Final graphical editing was performed using Adobe
222 Illustrator.

223

224 ***Molecular cloning and generation of HEK293 cell lines***

225 The protocols for cloning, cell line generation, and culturing have been previously described
226 (Andersson et al. 2016; Corcoran et al. 2014; Yuvaraj et al. 2021). Briefly, OR (and Orco)
227 genes with added 5' Apa1 and 3' Not1 restriction sites, *cacc* Kozak sequence, and N-terminal
228 epitope tags (Myc for Orco, V5 for ORs) were ligated into the pcDNATM4/TO (Orco) or
229 pcDNATM5/TO (ORs) mammalian expression vectors (Thermo Fisher Scientific). For OR
230 genes that required codon optimization for functional expression in HEK293 cells (Roberts et
231 al. 2021a), the nucleotide sequences were submitted to the Thermo Fisher Scientific GeneArt
232 Portal and codon optimized for *Homo sapiens*, excluding the start methionine and the epitope
233 tag, then synthesized and ligated into the pcDNATM5/TO expression vector. Because we had
234 no access to biological material from *D. ponderosae*, the two functionally assayed DponOR
235 genes were synthesized as codon optimized versions directly, and also because several
236 wildtype beetle OR genes are not functionally expressed in HEK cells (Roberts et al. 2021a).
237 A codon optimized gene of HabiOR4 was also tested since Western blots (below) failed to
238 detect this protein from cells transfected with the wildtype gene. Receptors encoded by
239 wildtype genes that were detected by Western blot were not codon optimized because they all
240 showed band intensities similar to, or higher than, several ORs previously characterized in
241 this system (Yuvaraj et al. 2018; Yuvaraj et al. 2021). Sequences of codon optimized genes
242 from the two species are provided in Supplementary Table 1. Sequences of OR genes cloned
243 from antennal cDNA (ItypOR5, ItypOR6, HabiOR3, and HabiOR4) have been deposited in
244 GenBank under the accession numbers OL865310-OL865313.

245

246 OR genes in expression vectors were transformed into HB101 ampicillin-resistant competent
247 cells (Promega), plated on ampicillin-containing agar, and incubated overnight at 37 °C.

248 Resulting colonies were PCR-screened with vector-specific primers, spread onto a new plate,
249 and incubated at 37 °C for 4-6 hours. Positive colonies were sub-cultured overnight at 37°C in
250 LB broth containing ampicillin. Plasmid DNA from the overnight cultures was harvested via
251 extraction with the PureLinkTM HiPure Plasmid Filter Midiprep kit (Thermo Fisher
252 Scientific), and insert sequence was confirmed by Sanger sequencing at the on-site DNA
253 Sequencing Facility (Dept. Biology, Lund University) using the BigDye® Terminator v1.1
254 Cycle Sequencing Kit (Thermo Fisher Scientific). Positive plasmids were linearized with
255 FspI, PciI, or BstZ17I (New England Biolabs, Ipswich, MA, United States) restriction
256 enzymes and incubated overnight at 37 °C.
257
258 Linearized plasmids containing the ItypOrco gene were transfected into HEK293 cells
259 containing a tetracycline-inducible repressor (TREx) using Lipofectamine 2000 (Thermo
260 Fisher Scientific) (Corcoran et al. 2014). Twenty-four hours post-transfection, antibiotics
261 (blasticidin for TREx, zeocin for Orco; both NEB) were added to select successfully
262 transfected cells. Once a stable cell line was generated, protein expression of the ItypOrco
263 gene was confirmed via Western blot analysis and functionality of Orco was confirmed using
264 the Orco agonist VUAA1 (described below) (Jones et al. 2011). We recently found that the
265 DponOrco gene is not functionally expressed in HEK cells (Roberts et al. 2021a); we
266 therefore co-expressed the DponOR genes with the ItypOrco gene to allow functional
267 characterization of these ORs. For consistency, the HabiOR genes were also tested together
268 with the ItypOrco. Due to the conserved function of Orco and the relatedness among the three
269 beetle species, we assumed that this strategy would not affect the OR response specificities.
270 This assumption is supported by previous studies showing that combinations of OR and Orco
271 proteins from different taxa assemble into functional receptor complexes responding properly
272 to known ligands (Corcoran et al. 2018). The linearized OR gene-containing plasmids were

273 transfected into the stably expressing TREx/ItypOrco cell line as described above, and
274 cultured with the antibiotic hygromycin (Gold BioTech) to select successfully transfected
275 cells. Resulting cell lines were frozen at –80 °C before functional assays.
276
277 ***Protein extraction and Western blot analysis***
278 Cells were cultured without antibiotics for 24 hours before the expression of Orco and OR
279 genes was induced with doxycycline (Sigma). At 16 hours post-induction, cells were pelleted
280 via centrifugation and total protein extraction was performed as described by Corcoran et al.
281 (2014). Protein extractions from non-induced cells served as negative controls. Western blot
282 was performed using 25 μg of total protein from each sample and standard protocols for
283 mixed molecular weight proteins. Primary antibodies (rabbit anti-Myc for Orco, rabbit anti-
284 V5 for ORs) were added at a ratio of 1:2000, and the secondary antibody (anti-rabbit +IgG,
285 HRP-linked for both Orco and ORs) was added at a ratio of 1:5000 (all antibodies from Cell
286 Signaling Technology), as described by Andersson et al. (2016).
287
288 ***Functional characterization of odorant receptors***
289 Ligand-binding activity of cell lines co-expressing Orco and ORs was tested via a calcium
290 fluorescence assay using a CLARIOstar Omega plate reader (BMG Labtech, Ortenberg,
291 Germany) according to previously described protocols (Andersson et al. 2016; Corcoran et al.
292 2014; Yuvaraj et al. 2021). Briefly, cells were plated in black-walled poly-D-lysine coated 96-
293 well plates (Corning Costar) and incubated overnight. Cells in half the wells were treated with
294 doxycycline to induce expression of exogenous Orco and OR genes 16 hours prior to testing,
295 leaving the non-induced cells as negative controls. The calcium-sensitive fluorophore Fluo-
296 4AM (Life Technologies) was loaded into all wells, and plates were incubated in the dark at

297 room temperature for 30 min before being washed with assay buffer, then incubated for
298 another 30 min in the dark at room temperature prior to the assay.
299
300 The test odor panel included 62 compounds (Supplementary Table 2) that are ecologically
301 relevant for conifer-feeding curculionids, including pheromone compounds, volatiles from
302 conifers and angiosperms as well as odorants produced by bark beetle fungal symbionts
303 (Kandasamy et al. 2019; Kandasamy et al. 2021; Yuvaraj et al. 2021). The Orco agonist
304 VUAA1 was tested (at 50 μM) on each cell line as a positive control for functional Orco
305 expression. Test odors were diluted in DMSO and assay buffer with a final concentration of
306 30 μM in the plate wells for screening experiments. Compounds were tested over a minimum
307 of three biological replicates (plates), and were pipetted into three induced and three non-
308 induced wells per plate, creating three technical replicates per plate. A negative control of
309 0.5% DMSO in assay buffer (vehicle) was tested on each cell line. Background fluorescence
310 was measured for both induced and non-induced cells immediately before compounds were
311 added to the wells, with ligand-binding response of cells measured as the percentage increase
312 in fluorescence from background readings 10 s post stimulation. Mean responses of cells to
313 the added ligands were calculated using GraphPad Prism 6 (GraphPad Software Inc., La Jolla,
314 CA, United States).
315
316 A response of ≥1% increase in fluorescence in induced cells was required for a compound to
317 be considered active, provided a significantly higher response in induced compared to non-
318 induced cells. Hence, a general linear model (GLM) with "induction" as a fixed factor and
319 "plate" as a random factor (to account for inter-plate variation) was performed using IBM
320 SPSS statistics v.25. Bonferroni correction to maintain the α-level at 0.05 (for up to 12
321 multiple comparisons within a cell line) was undertaken to avoid reporting false positives

322 (Type I statistical error). Compounds eliciting an increase in fluorescence of 3% or more at
323 the 30 μM screening concentration were tested in subsequent dose-response experiments.
324 Half-maximal effective concentrations (EC_{50}) were calculated using the non-linear curve fit
325 regression function in GraphPad Prism (version 6). Calculations of EC_{50} values were only
326 performed for compounds with (reasonably) sigmoid dose-response curves.
327

328 # Results

329 ***HabiOR annotation, expression, and phylogenetic analysis of ORs***

330 The HabiOrco gene and 78 HabiOR genes were annotated from the antennal transcriptome
331 assembly, of which 51 transcripts encoded full length proteins. The 28 partial HabiORs
332 encompassed 174 to 397 amino acids. Three of the ORs were extended by joining overlapping
333 sequences from two different transcripts. Annotation details and sequences of the HabiORs
334 are presented in Supplementary Table 3. Sequence reads from the male and female samples
335 were mapped to the open reading frames (ORFs) of annotated OR genes for estimation of
336 relative OR gene expression levels. This analysis showed that the HabiOrco gene is clearly
337 more highly expressed than any of the 78 HabiORs (Supplementary Table 3). The ORs
338 showed a range of expression levels (from 0.03% to 4.2% of the Orco expression in males;
339 from 0% to 5.7% in females), with no specific OR standing out as being particularly highly
340 expressed compared to the others. Expression was similar in the two sexes; the only putative
341 exceptions being the partial HabiOR27NC and HabiOR46NC that showed twice the
342 expression in females compared to males, and HabiOR48 with twice the expression in males
343 compared to females. Expression levels of the functionally characterized HabiOR3 and
344 HabiOR4 were intermediate, with a somewhat higher estimate for HabiOR4 in both sexes.
345

346 Recently, a phylogenetic analysis of the ORs across several coleopteran superfamilies defined
347 and revised nine main monophyletic groups of ORs (Mitchell et al. 2020). Our phylogenetic
348 analysis including ORs from the Curculionidae and Cerambycidae shows that the distribution
349 of HabiORs among the nine OR groups is similar to that of the other two curculionids (*I.*
350 *typographus* and *D. ponderosae*) in the analysis (Figure 1), with most (55) ORs located within
351 Group 7, followed by Group 1 (9 ORs), Group 5A and 2A (5 ORs in each), and 2B (4 ORs).
352 The main differences between *H. abietis* and the two bark beetle species are the stronger bias
353 of HabiORs towards Group 7, including a large HabiOR-radiation of 26 receptors
354 (HabiOR23-HabiOR48), and comparatively few HabiORs in Group 5A. The latter may be
355 explained by the generally poor antennal expression of Group 5A ORs (Yuvaraj et al. 2021);
356 indeed, the vast majority of Group 5A ORs from *D. ponderosae* was not found in the initial
357 transcriptome analyses (Andersson et al. 2013), but later recovered from the genome
358 (Andersson et al. 2019). As with other curculionids, our analysis indicates that *H. abietis*
359 entirely lacks ORs from Groups 3, 4, 5B, and 6. Similar to our previous study, the OR
360 phylogeny did not recapitulate the monophyly of Group 2B, which is likely explained by the
361 few species and narrow taxonomic range sampled in this study (Yuvaraj et al. 2021).
362
363 Our OR phylogeny suggests 12 highly supported clades of simple (1:1:1) OR orthologues
364 conserved across the three curculionids (Figure 1). We also found that two of the McarORs
365 appear to have representative orthologues in at least some curculionids, i.e., McarOR2
366 grouped together with HabiOR1 and ItypOR11, and McarOR4 with DponOR6NTE and
367 ItypOR51 (Figure 1). Within OR Group 2B, two orthologous groups of curculionid ORs
368 (ItypOR5/DponOR9/HabiOR4 and ItypOR6/DponOR8/HabiOR3) were positioned close to
369 McarOR5, responding to 2-PE –a pheromone component in this species (Figure 1). Hence,
370 these six ORs were targeted for functional characterization to investigate whether

371 evolutionarily related beetle ORs within and between coleopteran superfamilies may have the
372 same response specificities. The amino acid identities between ItypOR5, DponOR9, HabiOR4
373 range from 50.5% to 57.8%, and for ItypOR6, DponOR8, and HabiOR3 between 60.0% and
374 67.5%.
375
376 ***Conserved responses to green leaf volatiles and 2-phenylethanol in OR orthologues***
377 The HEK cells transfected with each of the six above-mentioned beetle OR genes were
378 analyzed for OR protein detection using Western blots. Except for HabiOR4, the OR proteins
379 were clearly detected, and only from cells induced to express the exogenous receptor genes,
380 demonstrating proper regulation by the repressor system (Supplementary Figure 1). Gene
381 sequences codon-optimized for expression in human cells were used for the DponORs
382 because we had no access to biological material from this species (Roberts et al. 2021a).
383 Additionally, because the HabiOR4 protein was not detected from cell lines transfected with
384 the wildtype OR gene, this gene was also codon-optimized and used in functional assays. The
385 superscript HsCO (*Homo sapiens* Codon Optimized) was added to the names of codon
386 optimized OR genes.
387
388 In the OR phylogeny, the orthologous curculionid ORs HabiOR4, ItypOR5, and DponOR9
389 group most closely to the 2-PE receptor in the cerambycid *M. caryae* (McarOR5; Figure 1).
390 Screening experiments testing 62 ecologically relevant compounds at 30 µM concentration
391 showed that neither of these curculionid ORs responded to 2-PE. Instead, HabiOR4^{HsCO}
392 responded to five six-carbon green leaf volatile (GLV) alcohols, abundant in angiosperm non-
393 host plants, with significantly stronger responses in induced *vs.* non-induced cells (Figure
394 2A). *Z*3-hexenol elicited the strongest response in the screening experiments (7.3% increased
395 fluorescence; $F_{1,14} = 183.8$; $p < 0.001$), followed by slightly weaker and similar responses to

396 each of *E*2-hexenol, *Z*2-hexenol, and 1-hexanol (5.2-5.7%; $F_{1,14} = 48.9$-118.8; all $p < 0.001$),
397 and a yet weaker response to *E*3-hexenol (3.6%; $F_{1,14} = 40.5$; $p < 0.001$). Subsequent dose-
398 response experiments largely recapitulated the screening data in terms of response magnitudes
399 elicited by the five compounds at the higher concentrations (Figure 2B). Nevertheless, these
400 experiments indicated similar sensitivities to the four most active ligands (EC_{50} values: *Z*3-
401 hexenol – 7.99 µM, *E*2-hexenol – 3.88 µM, 1-hexanol – 2.85 µM, and *Z*2-hexenol – 7.34
402 µM), whereas the sensitivity to *E*3-hexenol was lower as shown by its weaker response at
403 most tested concentrations and the non-sigmoid shape of the dose-response curve (EC_{50} could
404 not be estimated).
405
406 A similar response profile was apparent for DponOR9^{HsCO} (Figure 2C). Again, *Z*3-hexenol
407 elicited the highest response in the screening experiments (4.5%; $F_{1,14} = 51.5$; $p < 0.001$),
408 followed by *E*2-hexenol (3.2%; $F_{1,14} = 44.2$; $p < 0.001$), *Z*2-hexenol (2.3%; $F_{1,14} = 48.3$; $p <$
409 0.001), and 1-hexanol (2.0%; $F_{1,14} = 24.6$; $p < 0.001$). The slightly increased fluorescence seen
410 upon stimulation with *E*3-hexenol was not statistically significant after correction for multiple
411 statistical comparisons. In contrast to HabiOR4, (+)-*trans*-4-thujanol elicited a significant
412 response in DponOR9^{HsCO} (3.5%; $F_{1,14} = 17.0$; $p = 0.001$); however, half of this response was
413 also evident in the non-induced control cells suggesting that factors unrelated to the DponOR
414 contributed to the cells' response. The two GLV compounds eliciting responses above 3%
415 increased fluorescence in the screening were further examined in dose-response trials,
416 showing somewhat stronger responses to *Z*3-hexenol as compared to *E*2-hexenol at the higher
417 concentrations but similar responses at intermediate and lower concentrations (Figure 2D).
418 EC_{50} values could not be estimated due to the non-sigmoid shape of the dose-response curves,
419 which is commonly seen for ORs with comparatively low response magnitudes (Roberts et al.
420 2021a).

421

422 ItypOR5 responded to the same four GLV alcohols as did DponOR9^{HsCO}, albeit with overall
423 lower response magnitudes (Figure 2E), which is in accordance with this OR being detected
424 as a fainter band on Western blot (Supplementary Figure 1) compared to the other orthologues
425 (see also Roberts et al. 2021a). The rank order between compounds was slightly different,
426 with *E*2-hexenol eliciting the highest response (3.3%; $F_{1,24} = 39.8$; $p < 0.001$), followed by
427 *Z*2-hexenol (2.2%; $F_{1,23} = 19.3$; $p < 0.001$), and similar responses to *Z*3-hexenol (1.6%; $F_{1,24} =$
428 27.9; $p < 0.001$) and 1-hexanol (1.6%; $F_{1,24} = 30.5$; $p < 0.001$). As with DponOR9^{HsCO}, the
429 slightly increased fluorescence elicited by *E*3-hexenol in induced cells was not statistically
430 significant after correction for multiple comparisons. *E*2-hexenol activated ItypOR5 in a dose-
431 dependent manner (Figure 2F; EC_{50} could not be estimated due to the shape of the dose-
432 response curve); the other GLVs were not assayed in dose-response experiments due to their
433 screening responses being below 3%.

434

435 Compared to the GLV-responding ORs, the orthologous receptors HabiOR3, ItypOR6, and
436 DponOR8 are positioned a bit further away from McarOR5 in the OR phylogeny; yet they are
437 part of the same OR clade (Figure 1). The three ORs all responded exclusively to 2-PE, with
438 significantly stronger responses in induced compared to non-induced cells. The highest
439 response was recorded for HabiOR3 (10.5% increased fluorescence; $F_{1,19} = 324.7$; $p < 0.001$;
440 Figure 3A), followed by ItypOR6 (5.7%; $F_{1,14} = 85.9$; $p < 0.001$; Figure 3E), and
441 DponOR8^{HsCO} (4.0%; $F_{1,14} = 80.4$; $p < 0.001$; Figure 3C). Each of these receptors responded
442 to 2-PE in a dose-dependent manner with estimated EC_{50} values at 8.54 µM, 3.45 µM, and
443 5.12 µM for HabiOR3, ItypOR6, and DponOR8^{HsCO}, respectively (Fig. 3B, D, F).

444

445 # Discussion

446 To allow for functional characterization of *H. abietis* ORs, antennal transcriptomes were
447 sequenced and the ORs annotated, suggesting a similarly sized OR repertoire (79 ORs) as in *I.*
448 *typographus* (73 ORs) and *D. ponderosae* (86 ORs) (Andersson et al. 2019; Yuvaraj et al.
449 2021). The largest number of HabiORs was found in OR Group 7, and *H. abietis* stands out
450 by its large OR-radiation within this group. This differs from both the bark beetles and the red
451 palm weevil *R. ferrugineus,* but displays similarity with the large radiation of Group 7 ORs in
452 the sweetpotato weevil *Cylas formicarius* (Antony et al. 2016; Bin et al. 2017). Our previous
453 study indicated that the two scolytine bark beetles *I. typographus* and *D. ponderosae* share 17
454 highly-supported simple OR orthologues (Yuvaraj et al. 2021). Here, we included also the
455 pine weevil from the Molytinae subfamily in the analysis, and found that 12 simple
456 orthologues are conserved across these three species. The observation of fewer orthologues in
457 this broader analysis is consistent with the general positive correlation between species
458 relatedness and occurrence of OR orthology (Mitchell et al. 2020). Our OR phylogeny also
459 support the notion that OR orthology is rare across beetle superfamilies (Mitchell &
460 Andersson 2020; Mitchell et al. 2020).
461
462 To investigate whether OR orthologues are functionally conserved in the three curculionids,
463 and whether evolution of OR functionality may be traced beyond the beetle superfamily level,
464 we characterized two curculionid OR clades within beetle OR subfamily 2B, both of which
465 are evolutionarily related to the cerambycid 2-PE receptor McarOR5 (Mitchell et al. 2012).
466 Our results show conserved functions across the tested OR orthologues, with one group
467 (HabiOR3/DponOR8/ItypOR6) responding exclusively to 2-PE, even though several
468 structurally similar compounds also were tested (Supplementary Table 2). The other group
469 (HabiOR4/DponOR9/ItypOR5) responded to several six-carbon GLV alcohols. Our results
470 further show that the 2-PE receptors in the curculionids share a common ancestor with

471 McarOR5, which is also the case for their GLV-responding ORs. Interestingly, the GLV
472 receptors in the curculionids are the most closely related to McarOR5, while their 2-PE
473 receptors are part of a sister clade. This suggests that the response to 2-PE may be ancestral
474 and that new functions such as GLV-responsiveness have subsequently evolved
475 (neofunctionalization) in the more recent OR lineages of the curculionids. Another possibility
476 would be that the ancestral receptor was broadly tuned to both 2-PE and GLVs and that the
477 more recent OR lineages, derived from gene duplication, may have evolved higher specificity
478 for either GLVs or 2-PE in the process of subfunctionalization (Andersson et al. 2015).
479 Revealing the responses of the remaining six related McarORs (McarORs 8, 10, 13, 22, 39,
480 and 56; see Figure 1) is needed to conclusively inform the evolutionary history of these OR
481 functions; in particular in this context, it could be enlightening to search for GLV-responding
482 ORs among the orphan McarORs. The clade containing the curculionid 2-PE receptors is also
483 intriguing due to the presence of orthologues in numerous additional species from several
484 beetle families, including *Anoplophora glabripennis* (Cerambycidae), *R. ferrugineus*
485 (Curculionidae), *Leptinotarsa decemlineata* (Chrysomelidae), *Tribolium castaneum*
486 (Tenebrionidae), *Nicrophorus vespilloides* (Silphidae), and *Onthophagus taurus*
487 (Scarabaeidae) (Antony et al. 2021; Mitchell et al. 2020). Unraveling the functions of the
488 orthologues in these species should inform how widely conserved the ORs for 2-PE are across
489 the Coleoptera. In moths, it was shown that OR orthologs detecting the flower compound
490 phenylacetaldehyde were functionally conserved across eleven species from several families
491 of the Glossata suborder although the majority of the other investigated orthologues were
492 functionally divergent, even among related species (M. Guo et al. 2021).
493
494 The strong functional conservation among the examined OR orthologues suggests that 2-PE
495 and GLV alcohols convey important fitness-related information to the three curculionids.

496 Indeed, GLVs are abundant in the leaves of angiosperms and less so in conifers, and are
497 regarded as non-host cues that typically inhibit the attraction of conifer-feeding bark beetles
498 to their aggregation pheromones (reviewed in Zhang & Schlyter 2004). Hence, GLVs are
499 likely used by the beetles to avoid colonizing angiosperm trees in which they cannot
500 reproduce (Dickens et al. 1992; Schiebe et al. 2011). A role of GLVs in host choice has also
501 been proposed for *H. abietis* (Kännaste et al. 2013; Pettersson et al. 2008).
502
503 Also 2-PE is tightly connected to the chemical ecologies - and potentially reproductive fitness
504 - of the three investigated species. In *H. abietis* it is a potent anti-feedant, present in the gut of
505 the beetle and in non-host plants (Axelsson et al. 2017; Eriksson et al. 2008). Through
506 deposition of feces containing 2-PE over the laid eggs, the compound may contribute to
507 reducing egg predation by conspecifics (Axelsson et al. 2017; Borg-Karlson et al. 2006). It is
508 also present in the guts of both *D. ponderosae* and *I. typographus*. 2-PE inhibits attraction to
509 the aggregation pheromone in the former species, suggesting it may contribute to termination
510 of aggregation and induction of dispersal (Pureswaran et al. 2000). In contrast, 2-PE appears
511 to have no effect on pheromone attraction in *I. typographus* (Schlyter et al. 1987); however, it
512 is part of the odor blends released by several species of ophiostomatoid symbiotic fungi,
513 which are attractive to beetles in laboratory bioassays (Kandasamy et al. 2019). These fungi,
514 inoculated by beetles inside their galleries under the tree bark, are likely to benefit beetles by
515 providing nutrients and through metabolism of the tree's chemical defenses (Kandasamy et al.
516 2019; Kandasamy et al. 2021).
517
518 Since the ORs underlie the responses of the OSNs in the insect antennae, it is of interest to
519 compare OR responses from *in vitro* heterologous systems with those of putatively
520 corresponding OSN classes. Among the study species, *I. typographus* provides the best

521 example due to the extensive electrophysiological studies that have been conducted
522 (Andersson et al. 2009; Kandasamy et al. 2019; Kandasamy et al. 2021; Schiebe et al. 2019;
523 Tømmerås 1985). In relation to the GLV alcohols, one OSN class (named 'GLV-OH') that
524 responds most strongly and with similar sensitivity to *E*2-hexenol, *Z*3-hexenol, and 1-hexanol
525 has been identified in *I. typographus* (Andersson et al. 2009; Kandasamy et al. 2019). This
526 response profile resembles the ones from the GLV-responsive ORs characterized here,
527 although several additional compounds elicited weaker secondary responses in the OSN.
528 These secondary compounds include six-carbon aldehydes, eight-carbon alcohols as well as
529 2-PE (a detailed OR/OSN comparison is shown in Supplementary Table 4). The fact that 2-
530 PE is one of the secondary compounds for the GLV-responsive OSN class may support the
531 above-mentioned scenario that higher specificity in the extant ORs towards GLVs or 2-PE
532 may have evolved from a more broadly tuned ancestral receptor. The three OSN-active GLVs
533 have similar inhibitory effects on pheromone attraction of *I. typographus* and the use of a
534 single compound (e.g., 1-hexanol) can replace a three-component GLV mixture at an
535 equivalent release rate without compromising the inhibitory effect (Unelius et al. 2014; Zhang
536 & Schlyter 2003). This effect on the behavior may be explained by the rather indiscriminate
537 response of ItypOR5 to several structurally similar GLV compounds (Andersson et al. 2009;
538 Raffa et al. 2016). Indeed, *I. typographus* has no other known OSN class that primarily
539 responds to GLVs, although these compounds also activate OSNs primarily tuned to the less
540 volatile compounds 3-octanol and 1-octen-3-ol (OSN class 'C8an') (Andersson et al. 2009;
541 Andersson et al. 2012b). In *D. ponderosae*, coupled gas chromatographic-
542 electroantennographic detection (GC-EAD) demonstrated antennal detection of the GLV
543 alcohols that activate DponOR9 (Huber et al. 2000; Wilson et al. 1996). The strongest
544 inhibitory effect on pheromone attraction was observed for *Z*3-hexenol and *E*2-hexenol
545 (Wilson et al. 1996), that is, the two compounds that elicited the strongest responses in

546 DponOR9. However, since (to our knowledge) no SSRs have been performed, it remains
547 unknown whether *D. ponderosae* also has only one OSN class that responds most strongly to
548 six-carbon GLV compounds. Likewise, SSR studies testing GLV compounds in *H. abietis*
549 appear to be missing in the published literature (Wibe et al. 1997). In contrast to *I.*
550 *typographus*, beetles feeding on angiosperms typically possess several different OSN classes
551 primarily tuned to GLVs, each with their unique response specificity (Andersson et al. 2012a;
552 Carrasco et al. 2019; Hansson et al. 1999; Larsson et al. 2001).
553
554 *I. typographus* also has an OSN class that primarily responds to 2-PE and secondarily to 2-
555 phenethyl acetate and a few more compounds with weaker activity, including 1-hexanol
556 (Kandasamy et al. 2019). Similar to ItypOR5, the secondary OSN responses were not evident
557 in any of the three 2-PE receptors characterized in the present study (Supplementary Table 4).
558 Higher response specificities in ORs when tested in HEK293 cells as compared to those seen
559 in putatively corresponding OSN classes have been observed also previously, such as for
560 ItypOR46 and ItypOR49, responding to the beetle-produced compounds ipsenol and
561 ipsdienol, respectively (Yuvaraj et al. 2021). The reasons for the discrepancies in specificity
562 remain unknown but could potentially be due to lower sensitivity of the HEK cell assay as
563 compared to SSR or a consequence of the "unnatural" cellular environment in HEK cells,
564 which may affect protein folding and hence access of ligands to their binding sites (see also
565 Hou et al. 2020; Yuvaraj et al. 2022).
566
567 In conclusion, we report the functional characterization of six ORs from three species of the
568 Curculionidae family, including the first characterized ORs from the devastating forest pests
569 *H. abietis* and *D. ponderosae.* We reveal highly conserved responses to ecologically relevant
570 odors within the two groups of assayed OR orthologues, suggesting that the detection of 2-PE

571 and GLVs is important for the fitness of conifer-feeding curculionids. The characterized ORs
572 were shown to be evolutionarily related with the 2-PE receptor in *M. caryae*, sharing a
573 common ancestral OR protein. Our findings demonstrating conserved responses among beetle
574 ORs from two taxonomic superfamilies provide new insight into the functional evolution of
575 the OR family in this large insect order.

576

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587

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Data Accessibility and Benefit-Sharing

Data accessibility: The *H. abietis* RNAseq reads have been deposited in the SRA database at NCBI under the BioProject accession number PRJNA783427 (Powell, 2021). Sequences of cloned OR genes ItypOR5, ItypOR6, HabiOR3, and HabiOR4 have been deposited in GenBank under the accession numbers OL865310-OL865313 (Roberts et al., 2021b). Raw data from all HEK cell assays are reported in the supplementary materials of this article.

Benefit-Sharing: Not applicable

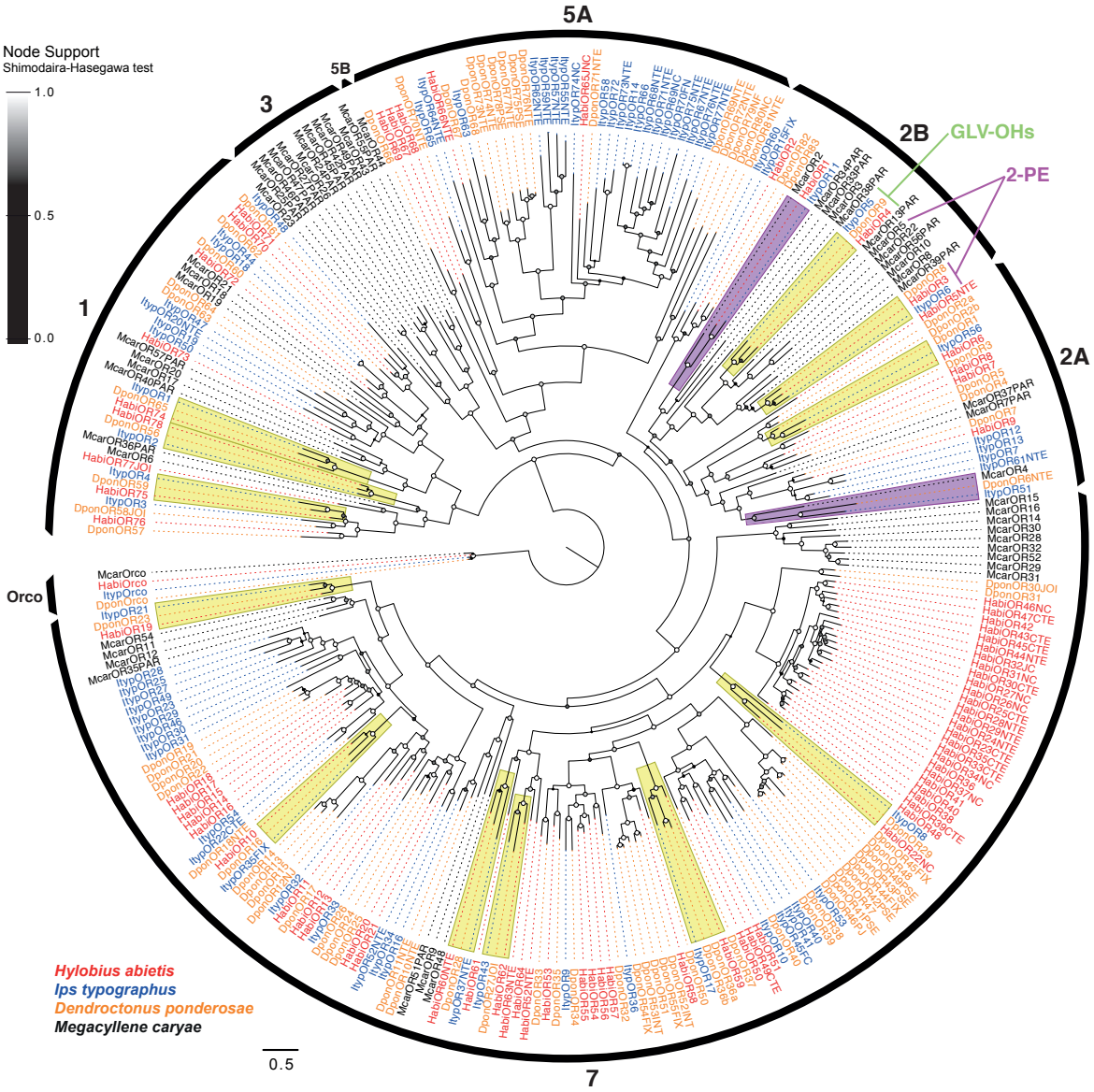
Author contributions

MNA conceived the project. RER and MNA conceptualized and designed the study. RER, TB, JKY, and MNA performed molecular work. RER, TB, and JKY performed cell culturing and experimental assays. EG-W, BSH, and MNA coordinated the sequencing of *H. abietis*. EG-W and DP performed transcriptome assemblies, with DP assessing OR gene expression and completeness of final assemblies. MNA annotated the HabiORs, constructed the OR phylogeny, and performed statistical analysis of the HEK cell data. MNA, JKY, and CL

880 contributed to project supervision. MNA and RER drafted the manuscript. All authors
881 contributed to the final version of the manuscript, and have read and approved it for
882 submission.
883
884 **Figure Legends**
885
886 **Figure 1. Maximum likelihood phylogeny of odorant receptors (ORs) from beetles of**
887 **Curculionidae and Cerambycidae.** Included are OR amino acid sequences from the
888 curculionids *Hylobius abietis* ('Habi'; red), *Ips typographus* ('Ityp'; blue), *Dendroctonus*
889 *ponderosae* ('Dpon'; orange), and the cerambycid *Megacyllene caryae* ('Mcar'; black). The
890 tree is based on a MAFFT alignment, constructed using FastTree, and rooted with the
891 conserved Orco lineage. The major coleopteran OR groups are indicated by the black arcs
892 (Mitchell et al. 2020). The twelve groups of simple (1:1:1) OR orthologues across the three
893 curculionids are highlighted in yellow; two clades housing putative simple orthologues shared
894 by the cerambycid *M. caryae* and two of the curculionids are highlighted in purple. Receptors
895 in OR group 2B that were functionally characterized in the present study and the previously
896 characterized McarOR5 (Mitchell et al. 2012) are labeled by the compounds that activate
897 them (GLV-OHs = green leaf volatile alcohols; 2-PE = 2-phenylethanol). Local node support
898 values were calculated using the Shimodaira-Hasegawa (SH) test implemented in FastTree,
899 and are indicated on branch nodes by the shaded circles; support increases with the brightness
900 of the circles. The sources of sequence data and explanation of receptor suffixes are detailed
901 in the Materials and Methods section.
902
903 **Figure 2. Conserved responses to green leaf volatile (GLV) alcohols in curculionid**
904 **odorant receptor (OR) orthologues. (A)** Response of *Hylobius abietis* OR4 (*Homo sapiens*
905 codon optimized; HabiOR4^{HsCO}) to select compounds in the screening experiments (30 µM
906 stimulus concentration; n = 3 biological replicates, n_{total} = 9). **(B)** Dose-dependent response of
907 HabiOR4^{HsCO} to the five active GLVs, indicating similar sensitivities to four of the
908 compounds (see main text for EC_{50} values; n = 3-5 biological replicates, n_{total} = 9-15). **(C)**
909 Screening responses of *Dendroctonus ponderosae* OR9 (*H. sapiens* codon optimized;
910 DponOR9^{HsCO}; n = 3 biological replicates, n_{total} = 9), and **(D)** dose-dependent responses of
911 DponOR9^{HsCO} to the two most active ligands (n = 5 biological replicates, n_{total} = 15). **(E)**
912 Screening response of *Ips typographus* OR5 (ItypOR5; n = 3-5 biological replicates, n_{total} = 9-
913 15), and **(F)** dose-dependent response of ItypOR5 to the most active ligand (n = 6 biological
914 replicates, n_{total} = 18). Ligand-induced activation was recorded from cells induced (+) to
915 express the exogenous Orco and OR genes and from non-induced (–) control cells. VUAA1
916 was tested at 50 µM as a control for functional Orco expression. Asterisks indicate
917 significantly stronger responses in induced compared to non-induced cells (at $p < 0.001$; see
918 main text for details on statistics). Ligands eliciting < 3% increased fluorescence in screening
919 assays were excluded from dose-response trials. Error bars show SEM. All data from induced
920 and non-induced cells to all 62 test compounds are reported in Supplementary Data 1.
921
922 **Figure 3. Conserved responses to 2-phenylethanol in curculionid odorant receptor (OR)**
923 **orthologues. (A)** Response of *Hylobius abietis* OR3 (HabiOR3) to select compounds in the
924 screening experiments (30 µM stimulus concentration; n = 3-4 biological replicates, n_{total} = 9-
925 12). **(B)** Dose-dependent responses of HabiOR3 (n = 3 biological replicates, n_{total} = 9; see

main text for EC_{50} value). **(C)** Screening responses of *Dendroctonus ponderosae* OR8 (*H. sapiens* codon optimized; $DponOR8^{HsCO}$; $n = 3$ biological replicates, $n_{total} = 9$), and **(D)** dose-dependent responses of $DponOR8^{HsCO}$ ($n = 9$ biological replicates, $n_{total} = 27$; see main text for EC_{50} value). **(E)** Screening responses of *Ips typographus* OR6 (ItypOR6; $n = 3$ biological replicates, $n_{total} = 9$), and **(F)** dose-dependent responses of ItypOR6 ($n = 3$ biological replicates, $n_{total} = 9$; see main text for EC_{50} value). Ligand-induced activation was recorded from cells induced (+) to express the exogenous beetle Orco and OR genes and from non-induced (–) control cells. VUAA1 was tested at 50 µM as a control for functional Orco expression. Asterisks indicate significantly stronger responses in induced compared to non-induced cells (at $p < 0.001$; see main text for details on statistics). Error bars show SEM. All data from induced and non-induced cells to all 62 test compounds are reported in Supplementary Data 1.

939 **Figure 1**



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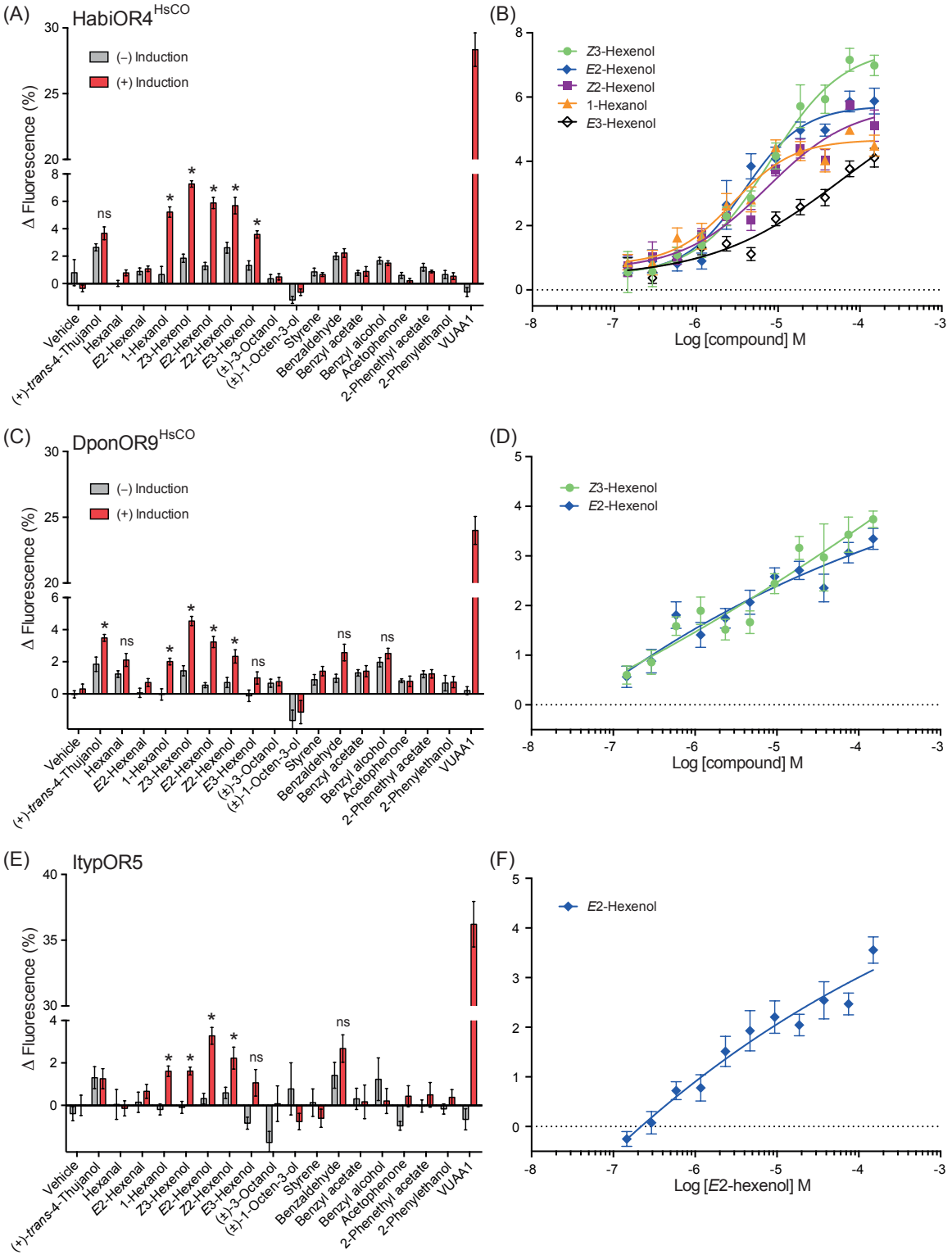
942 **Figure 2**



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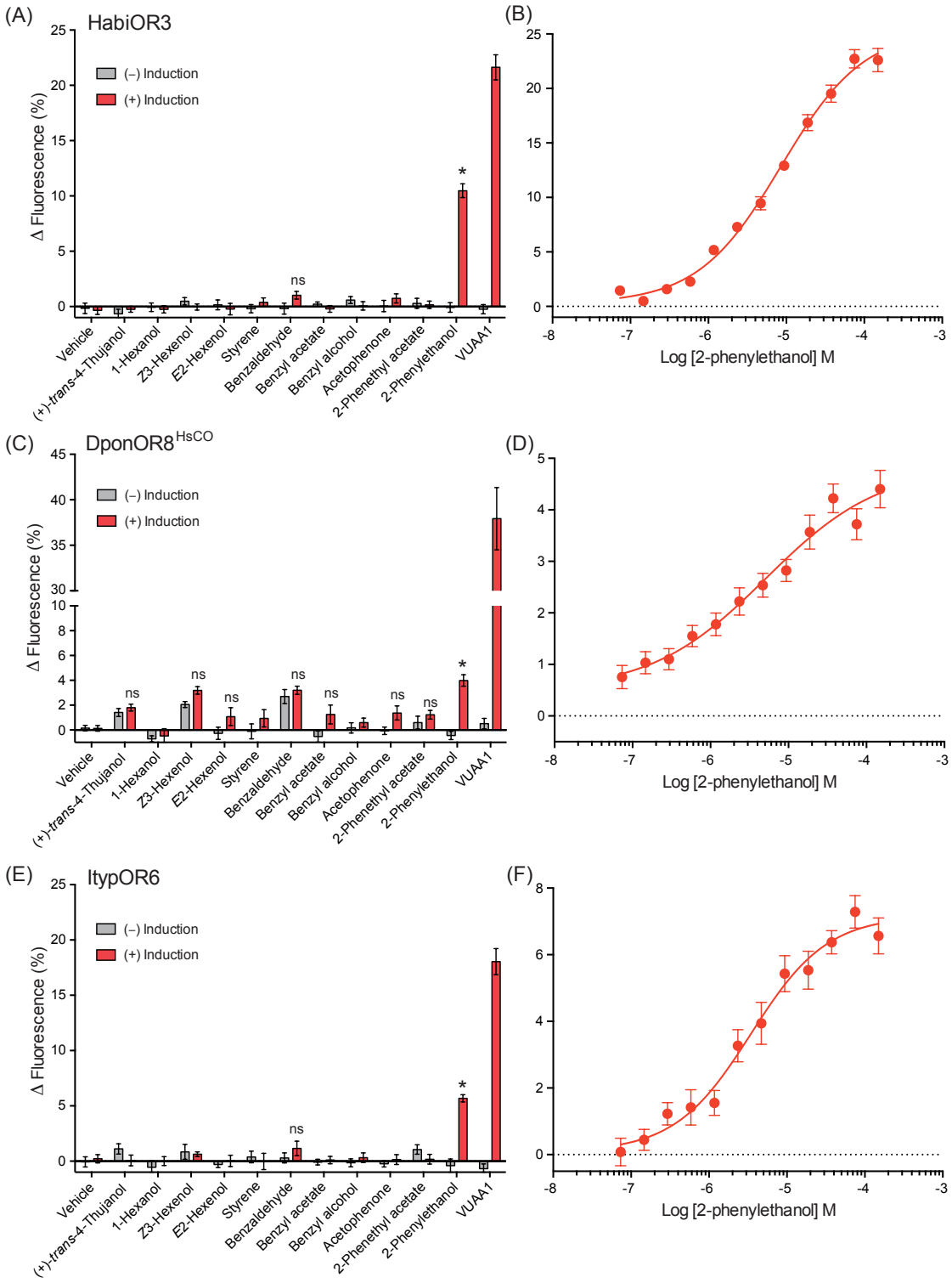
945 **Figure 3**



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