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1 THE PUPAL PARASITOID *TRICHOPRIA DROSOPHILAE* IS
2 ATTRACTED TO THE SAME YEAST VOLATILES AS ITS ADULT
3 HOST

4
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54 the lab of BL is supported by KU Leuven, VLAIO and FWO.

55

56 **ABSTRACT** - There is increasing evidence that microorganisms, particularly fungi and bacteria,
57 emit volatile compounds that mediate the foraging behaviour of insects and therefore have the
58 potential to affect key ecological relationships. However, to what extent microbial volatiles affect
59 the olfactory response of insects across different trophic levels remains unclear. Adult parasitoids
60 use a variety of chemical stimuli to locate potential hosts, including those emitted by the host's
61 habitat, the host itself and microorganisms associated with the host. Given the great capacity of
62 parasitoids to utilize and learn odours to increase foraging success, parasitoids of eggs, larvae or
63 pupae may respond to the same volatiles the adult stage of their hosts use when locating their
64 resources, but compelling evidence is still scarce. In this study, using *Saccharomyces cerevisiae*
65 we show that *Trichopria drosophilae*, a pupal parasitoid of *Drosophila* species, is attracted to the
66 same yeast volatiles as their hosts in the adult stage, i.e. acetate esters. Parasitoids significantly
67 preferred the odour of *S. cerevisiae* over the blank medium in a Y-tube olfactometer. Deletion of
68 the yeast *ATF1* gene, encoding a key acetate ester synthase, decreased attraction of *T. drosophilae*,
69 while addition of synthetic acetate esters to the fermentation medium restored parasitoid attraction.
70 Bioassays with individual compounds revealed that the esters alone were not as attractive as the
71 volatile blend of *S. cerevisiae*, suggesting that other volatile compounds also contribute to the
72 attraction of *T. drosophilae*. Altogether, our results indicate that pupal parasitoids respond to the
73 same volatiles as the adult stage of their hosts, which may aid them in locating oviposition sites.

74 **Keywords** - Acetate esters, behavioral response, *Drosophila*, parasitoid, *Saccharomyces*
75 *cerevisiae*, *Trichopria drosophilae*, tritrophic interaction

76

77 **Declarations**

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84 **Conflicts of interest/Competing interests**

85 The authors declare that no conflicts of interest exist.

86 **Availability of data and material**

87 Data and materials are available upon request.

88 **Code availability**

89 Codes for statistical analysis were written in R and are available upon request.

90 **Author contributions**

91 BL, HJ and ISS conceived the ideas and designed methodology. GD, FACVN, SB and BM-H
92 collected the data. JS and KJV contributed to equipment and reagents for the VOC analysis. KJV
93 provided the yeast strains, JA and FW provided insects. FACVN, HJ and BL analyzed the data.
94 HJ and BL led the writing of the manuscript. All authors contributed critically to the drafts of this
95 manuscript and gave final approval for publication.

96 **Ethical note**

97 Experimental manipulation of parasitoids occurred according to the common and ethical
98 requirements for animal welfare. All parasitoids were carefully handled during experiments and
99 maintained in the laboratory under appropriate conditions.

100 **Consent to participate**

101 Not applicable

102 **Consent for publication**

103 Consent for publication was granted by all co-authors.

104

INTRODUCTION

105 Microorganisms release a wide variety of volatile organic compounds (VOCs), many of which
106 play a crucial role in intra- and inter-kingdom interactions (Schulz-Bohm et al., 2017; Tilocca et
107 al., 2020). Given their high vapor pressure and low molecular weight, microbial volatile organic
108 compounds (mVOCs) can travel far from the point of production through the atmosphere, porous
109 soils and liquids, making them ideal info-chemicals for mediating both short- and long-distance
110 interspecific interactions (Bitas et al., 2013). Although knowledge about the biological and
111 ecological roles of mVOCs is still limited, there is increasing evidence that mVOCs mediate the
112 foraging behaviour of insects and therefore have the potential to affect key ecological relationships
113 (Davis et al., 2013; Leroy et al., 2011).

114 Recent research has shown that the production of insect-attracting metabolites is a basic
115 and general feature in yeasts (Becher et al., 2018). Yeast volatiles act as semiochemicals that attract
116 insects by signalling the presence of suitable resources such as sugary food or oviposition sites
117 (Davis et al., 2013; Dzialo et al., 2017). Furthermore, the yeasts themselves may provide an
118 important source of dietary proteins to the insects (Begon, 1982; Skorupa et al., 2008). This
119 chemical communication between yeasts and insects is believed to be the driving force of a strong
120 mutualistic relationship, also referred to as the “dispersal–encounter hypothesis” (Madden et al.,
121 2018). Early in their evolution, yeasts evolved biochemical pathways to obtain energy from sugars
122 during which volatile compounds (e.g. ethanol and other alcohols, and fruity acetate esters) are
123 produced as by-products (Dzialo et al., 2017). These volatiles thus signal the presence of sugar (or
124 are energy sources themselves (Ogueta et al., 2010)) and attract sugar-feeding insects which can
125 inadvertently transport the yeasts to another patch of sugar. The otherwise immotile yeasts benefit
126 from getting transported to new habitats, the insects from a free and honest signal indicating an

127 available resource (Becher et al., 2012; Christiaens et al., 2014). Furthermore, the yeasts can use
128 the insects to survive unfavourable environmental conditions like a cold winter (Pozo et al., 2018;
129 Stefanini et al., 2012). The benefits that yeasts might reap from this interaction may go beyond
130 mere dispersal and survival. Low nutrient levels trigger the formation of sexual spores that can
131 survive passage through the insect gut and promote outbreeding and thus genetic variation (Freese
132 et al., 2007).

133 Although the benefits of this mutualistic interaction have become better understood in
134 recent years, very little is known about potential costs for both partners. Both the yeasts and the
135 insects may experience direct and indirect costs related to the interaction. For example, production
136 of certain volatiles may be costly, or some yeast propagules may be killed by feeding insects.
137 Likewise, sugar resources with high yeast densities may have decreased sugar quantities and
138 qualities, or have high alcohol concentrations which may be detrimental for the insects (Bouletreau
139 & David, 1981; Madden et al., 2018). Insects may experience indirect costs when natural enemies
140 are attracted to the same yeast volatiles helping them to find their hosts. Parasitoids (i.e. insects
141 whose larvae feed and develop within or on the bodies of other arthropods, eventually killing them)
142 use a variety of chemical cues to identify and locate potential hosts, including those emitted by the
143 host's habitat (Vet et al., 1984), host by-products (e.g. frass, Agelopoulos et al., 1995), the host
144 itself (Jumean et al., 2009), and organisms living in close association with the host (Sullivan et al.,
145 2000) or its habitat (Goelen et al., 2020). Given the extraordinary capacity of parasitoids to detect
146 and associate chemical information with a reward (Turlings et al., 1992; Vet et al., 1995; Vet, et
147 al., 2002), it is reasonable to assume that they may exploit the same volatiles as their hosts to
148 optimize foraging behaviour, but compelling evidence is still lacking. There are studies showing
149 that egg and larval parasitoids of Tephritid fruit flies are not only attracted to host-containing

150 infested, fermenting fruits (Carrasco et al., 2005), but also respond to odours from healthy,
151 undamaged fruits which their adult hosts prefer for egg deposition (Altuzar et al., 2004; Eben et
152 al., 2000; Leyva et al., 2012).

153 The objective of this study was to test the hypothesis that pupal parasitoids respond to the
154 same yeast volatile compounds that the adult stage of their hosts use to locate suitable resources.
155 Specifically, we evaluated the olfactory response of *Trichopria drosophilae* to acetate ester
156 production in *Saccharomyces cerevisiae*. *Trichopria drosophilae* is a solitary, cosmopolitan pupal
157 endoparasitoid that attacks many species of Drosophilidae (Carton et al., 1986; Yi et al., 2020),
158 and is a very promising candidate for augmentative biocontrol of the invasive pest species
159 *Drosophila suzukii*, for which it is already commercially available (Gabarra et al., 2015; Mazzetto
160 et al., 2016). *Saccharomyces cerevisiae* was chosen as it is frequently used to study *Drosophila* –
161 yeast interactions (Arguello et al., 2013; Christiaens et al., 2014; Ha et al., 2009; Murgier et al.,
162 2019; Scheidler et al., 2015), and has been shown to produce acetate esters, particularly ethyl
163 acetate and isoamyl acetate, that attract adult *Drosophila melanogaster* flies (Christiaens et al.,
164 2014). To test the hypothesis that acetate esters also drive parasitoid attraction, Y-tube
165 olfactometer bioassays were performed using cell-free fermentation media of a wild type *S.*
166 *cerevisiae* strain and two mutants thereof in which the production of acetate esters was either
167 reduced or enhanced. Studying mutant organisms that have acquired changes or deletions in their
168 genome has the advantage of determining gene functions in a very efficient way, particularly in a
169 community context to unravel ecological functions of genes without affecting other genome
170 features (Christiaens et al., 2014). Our study not only provides new insights in the interactions that
171 take place between different trophic levels, but may also lead to new tools that enhance the
172 biocontrol efficacy of *T. drosophilae* against *D. suzukii* (Holighaus & Rohlf, 2016).

173

174

MATERIALS AND METHODS

175 **Study Organisms.** Three strains of *S. cerevisiae* (Basidiomycota: Saccharomycetaceae) that
176 differed in acetate ester production were used in this study. These included the wild type strain
177 Y182 (WT-Y182) and two *ATF1* mutants of Y182, one in which the *ATF1* gene was deleted (DEL-
178 KV3734) and one in which the *ATF1* gene is overexpressed (OE-KV3735) (Christiaens et al.,
179 2014). The *ATF1* gene is one of two genes (*ATF1* and *ATF2*) encoding an alcohol acetyl transferase
180 in *S. cerevisiae*, a key enzyme in the production of acetate esters from acetyl-coenzyme A and
181 alcohol. Among these two genes, *ATF1* controls the bulk of the acetate ester formation in *S.*
182 *cerevisiae* (Lilly et al., 2000; Verstrepen et al., 2003). Strain Y182 was originally isolated from a
183 vineyard and has an average production of acetate esters (Christiaens et al., 2014). In the *ATF1*
184 deletion mutant, both *ATF1* alleles were deleted using deletion cassettes based on pUG6,
185 conferring resistance to either hygromycin B or G-418 disulfate. In the overexpression mutant, the
186 native promoter is replaced by the strong, constitutive *TEF1* promoter, introduced using pYM-
187 N18, which contains the KanMX antibiotic resistance marker for mutant selection. Markers were
188 removed through the Cre/LoxP technique using pSH65. Deletions as well as marker removal were
189 confirmed through (lack of) growth on selective media, as well as PCR (Christiaens et al., 2014).
190 Strains were stored at -80°C in yeast extract peptone dextrose broth (YPDB; Difco, Le Pont-de-
191 Claix, France) containing 37.5 % glycerol.

192 *Trichopria drosophilae* (Hymenoptera: Diapriidae) is a widespread solitary pupal
193 endoparasitoid of *Drosophila* spp. (Carton et al., 1986; Yi et al., 2020). Adult females of *T.*
194 *drosophilae* are commonly encountered in the habitat of *Drosophila* flies, seeking *Drosophila*
195 pupae for oviposition. The vast majority of its *Drosophila* hosts lay eggs in damaged, overripe or

196 decaying fruit, where alcoholic fermentation abundantly occurs (Phaff & Starmer, 1987). Unlike
197 other species, female *D. suzukii* prefers to lay eggs in ripening fruit during the early stages of
198 fermentation (Walsh et al., 2011). When a suitable pupa is found, the parasitoid lays an egg in the
199 host hemocoel. The *T. drosophilae* larvae then feed on the tissues of the host, which are
200 subsequently killed (Carton et al., 1986).

201
202 **Fermentations.** Yeast fermentations were performed as outlined in Christiaens et al. (2014).
203 Briefly, fermentations were started by inoculating the yeasts from a YPD 2% plate into a test tube
204 with 5 mL YPDB 2%, and incubating the tubes at 30°C on a rotary shaker at 100 rpm. After one
205 overnight, 300 µL was inoculated into 50 mL YPDB 4% in a 250-mL Erlenmeyer flask, which
206 was then sealed with a water lock and incubated overnight at 30°C (100 rpm). Subsequently, the
207 OD₆₀₀ was measured and the preculture was used to inoculate a 250-mL Erlenmeyer flask
208 containing 150 mL YPD 10% at a final OD₆₀₀ of 0.5. Flasks were sealed with a water lock and
209 fermentations were allowed to continue for seven days at 30°C while shaking at 100 rpm.
210 Afterwards, fermentation media were spun down at 4,500 g for 5 min and subsequently filtered
211 (pore size 0.22 µm; Nalgene, Waltham, MA, USA) to obtain cell-free cultures. Obtained media
212 were then stored in small aliquots in sealed sterile dark glass vials (Fagron, Nazareth, Belgium) at
213 -20 °C until further use (VOC analysis and olfactometer bioassays). For each yeast strain, three
214 independent fermentations were performed, and a medium without yeast inoculation was included
215 as a control (sterility of the blank medium was confirmed after the incubation period).

216
217 **VOC Analysis.** To detect and determine the concentrations of various aroma compounds
218 associated with yeast fermentations, including higher alcohols and esters, a Headspace Gas

219 Chromatography system coupled with a Flame Ionization Detector (HS-GC-FID) was used. A
220 headspace autosampler (PAL system, CTC analytics, Switzerland) was used and the GC contained
221 a DB-WAXether column (length: 30 m; internal diameter: 0.32 mm; layer thickness: 0.50 μm)
222 (Shimadzu, Kyoto, Japan). Nitrogen was used as the carrier gas. For each sample, 5 mL was put
223 in a 20 mL glass vial containing 1.75 g of sodium chloride. The vials were immediately closed and
224 kept at -20°C until their analysis in order to minimize evaporation and loss of volatile compounds.
225 Prior VOC analysis, vials were thawed at room temperature for 30 min. During the
226 chromatographic run, each vial with sample was heated at 70°C with continuous agitation (500
227 rpm) for 25 min, inside a heater unit of the autosampler. After this incubation period, 1 ml of the
228 headspace sample was injected into the GC inlet using a 2.5-ml headspace syringe (Hamilton,
229 Switzerland). The injector and FID were both kept at 250°C . The GC oven temperature was first
230 held at 50°C for 5 min and then allowed to rise to 80°C at a rate of $5^{\circ}\text{C min}^{-1}$, followed by a second
231 ramp of $4^{\circ}\text{C min}^{-1}$ until 200°C . The temperature was then held for 3 min at 200°C and subsequently
232 increased by $4^{\circ}\text{C min}^{-1}$ until a temperature of 230°C was reached. Results were analyzed with the
233 Shimadzu GCSolution software version 2.43.00. Stock solutions of authentic volatile standards
234 (18 compounds) were prepared in ethanol. For all detected compounds, calibration curves were
235 made prior to sample analysis. To this end, solutions of the target compounds were prepared in
236 water by spiking the compounds while keeping 5% ethanol solution to obtain a 9-point calibration
237 curve.

238

239 **Olfactometer Bioassays.** To investigate the olfactory response of *T. drosophilae* to the different
240 fermentation media, naïve females (inexperienced to yeast smell and food; less than 24h old) were
241 tested in a Y-tube olfactometer bioassay. Parasitoids were obtained in the form of parasitized *D.*

242 *suzukii* pupae from Bioplanet (Cesena, Italy). Upon receipt, parasitized pupae were placed in a
243 nylon insect cage (20×20×20 cm, BugDorm, MegaView Science Co., Ltd., Taichung, Taiwan) and
244 kept under controlled conditions (22°C, 70% relative humidity and a 16:8-h light:dark
245 photoperiod) until parasitoid emergence. One hour prior testing, the parasitoid cage was brought
246 from the rearing chamber to the olfactometer laboratory for acclimatization. The olfactometer, a
247 glass Y-tube (base: 20 cm; arms:12 cm with a 60° angle at the Y-junction; inner diameter: 1.5 cm)
248 connected to an air pump producing an unidirectional air flow of 400 mL min⁻¹ from the arms to
249 the base, was put on a table that was homogeneously illuminated by four high frequency 24W T5
250 TL-fluorescent tubes with a 96% colour representation of true day light at a height of 0.45 m
251 (Goelen et al., 2020). To improve parasitoid responsiveness, the Y-tube was mounted at a 20°
252 incline stimulating insect movement towards the odour source. Additionally, to eliminate any
253 visual cues that could affect parasitoid response, the olfactometer was surrounded by white
254 curtains.

255 In a first set of experiments, parasitoid behaviour was evaluated by simultaneous
256 application of two odours in different conditions, including (i) odour of the blank medium vs water,
257 (ii) odour of the three yeast strains vs blank medium, (iii) odour of the *ATF1* deletion mutant
258 supplemented with acetate esters vs blank medium, and (iv) odour of the *ATF1* deletion mutant
259 supplemented with acetate esters vs the wild type strain or the *ATF1* overexpression mutant.
260 Experiments were performed with 1000× diluted cell-free fermentation medium as preliminary
261 experiments revealed suboptimal responses with higher concentrations (data not shown). The
262 supplemented samples of the *ATF1* deletion mutant contained either ethyl acetate (99.5%, Acros
263 Organics), isoamyl acetate (>95%, Sigma-Aldrich, Saint Louis, MO, USA) or phenylethyl acetate
264 (98%, Sigma-Aldrich) at concentrations that matched the ones present in the diluted media from

265 the wild type yeast (0.03 ppm, 0.0007 ppm and 0.0001 ppm, respectively) or the overexpression
266 mutant (0.1 ppm, 0.003 ppm and 0.0007 ppm, respectively), or combinations of these compounds
267 (Table 1). For each test, 150 μ L medium was loaded on a filter paper (37 mm; Macherey-Nagel,
268 Düren, Germany) and subsequently put in one of the olfactometer odour chambers. In a second set
269 of experiments, parasitoid response was evaluated by subjecting the parasitoids to two
270 concentrations of ethyl acetate (0.1 ppm and 1 ppm), isoamyl acetate (0.001 ppm and 0.01 ppm)
271 or phenylethyl acetate (0.001 ppm and 0.01 ppm) dissolved in diethyl ether vs diethyl ether. Again,
272 150 μ L was loaded on a filter paper, and 30 s later the filters were put in the odour chambers of
273 the olfactometer set-up.

274 All experiments were conducted with 60 female individuals, which were released in 12
275 cohorts of five individuals at the base of the olfactometer. Olfactory response was evaluated 10
276 min after their release. Wasps that had passed a set line in of one of the olfactometer arms (1 cm
277 from the Y-junction) at the time of evaluation were considered to have chosen the odour source
278 presented by that olfactometer arm (Goelen et al., 2020). All other parasitoids were considered as
279 non-responding individuals and were eliminated from statistical analysis. For every release, new
280 parasitoid females were used. To avoid positional bias, the arms of the Y-tube olfactometer were
281 flipped 180° every six releases. At the same time, the Y-tube was also renewed by a clean tube.
282 To maintain a high level of odour release, filter papers were replaced with fresh filter papers with
283 150 μ L of the tested medium every two runs. At the end of the experiment, all olfactometer parts
284 were thoroughly cleaned with tap water, distilled water, acetone and finally pentane. After solvents
285 had evaporated, the glass parts were placed overnight in an oven at 150°C. All bioassays were
286 conducted at $23 \pm 1^\circ\text{C}$ and $65 \pm 5\%$ RH between 09h00 and 16h00. As the VOC composition of

287 the three biological replicates was highly similar, olfactory response was determined for one of the
288 three biological replicates.

291

292 ***Statistical Analysis.*** Differences in VOC profiles between the different yeast strains were
293 visualized by a principal component analysis (PCA) using the concentrations of the detected
294 volatiles as dependent variables. Additionally, a non-parametric multivariate analysis of variance
295 (*PERMANOVA*) was used to investigate whether the VOC profiles differed between the different
296 yeast strains and the blank medium. We performed 9999 permutations to assess the significance
297 of the observed *pseudo F*-statistic. All calculations were performed using the *adonis* function of
298 the *vegan* package (Oksanen et al., 2013) in R. Parasitoid olfactory response was analyzed using
299 a *Generalized Linear Mixed Model (GLMM)* based on a binomial distribution with a logit link
300 function (logistic regression) using the test treatment ((supplemented) fermentation medium or
301 compound) as fixed factor (performed in R with the ‘*glmer*’ function from the *lme4* package).
302 Each release of one cohort of five parasitoid females served as a replicate ($n = 12$). To adjust for
303 overdispersion and to prevent pseudo-replication, the release of each cohort was included in the
304 model as a random factor. The number of parasitoids choosing the treatment side or the control in
305 each cohort was entered as response variable. To examine the preference of the parasitoids, we
306 tested the null hypothesis (H_0) that parasitoids showed no preference for any olfactometer arm (i.e.
307 50:50 response) by testing $H_0: \text{logit} = 0$, which equals a 50:50 distribution. In addition, an analysis
308 of variance *Type III Wald chi-square test* was performed on the *GLMM* to determine if there was
309 an overall difference between the olfactory responses for the different treatments. A significance
310 level of $\alpha = 0.05$ was used to determine significant attraction or repellence. The *GLMM* analysis
311 was performed in R (R Core Development Team, 2019).

312

313

RESULTS

314 **VOC Profiles.** Principal component analysis (PCA) showed a clear separation of the obtained

315 VOC profiles between the three yeast strains and the blank medium. The first principal component

316 (PC1) accounted for 60.6% of the total variation, the second component (PC2) for 21%. Yeast

317 strains were separated from the blank medium along the first axis, and were separated from each

318 other mainly along the second axis (Fig. 1). The overexpression mutant was characterized by high

319 concentrations of acetate esters (e.g. ethyl acetate, isoamyl acetate, isobutyl acetate and

320 phenylethyl acetate). The deletion mutant was characterized by relatively high concentrations of

321 1-hexanol (Fig. 1). *PERMANOVA* confirmed that the VOC profiles were significantly different

322 (*pseudo-F* = 62.2, *P* < 0.0001). Univariate analyses of variance indicated that the levels of various

323 acetate esters (ethyl acetate, isoamyl acetate, isobutyl acetate, phenylethyl acetate, and propyl

324 acetate) were significantly reduced or even completely abolished in the medium of the *ATF1*

325 deletion mutant, whereas they were abundantly produced by the overexpression mutant (Table 1).

326 Likewise, the VOC blend of the deletion mutant was enriched in a number of alcohols which are

327 acetate ester precursors (isoamyl alcohol, isobutanol, 1-hexanol and 1-propanol). No significant

328 differences in the concentration of other volatile compounds were observed among the three yeast

329 strains (Table 1).

330

331 **Parasitoid Olfactory Response.** Olfactory response of *T. drosophilae* varied significantly between

332 the three yeast strains (*GLMM*; $\chi^2 = 13.5936$; *df* = 2; *P* = 0.001; Fig. 2). Parasitoids had a significant

333 preference for the wild type strain (*P* < 0.001) and the *ATF1* overexpression mutant (*P* < 0.001),

334 while a neutral response was obtained for the *ATF1* deletion mutant (Fig. 2). To verify whether

335 the observed behavioral differences were due to the lower acetate ester levels produced by the
336 *ATF1* deletion mutant, the *ATF1* deletion mutant medium was supplemented with three important
337 acetate esters affected by *ATF1* deletion (Table 1), i.e. ethyl acetate, isoamyl acetate or phenylethyl
338 acetate, and combinations of these compounds. Compounds were added in concentrations that
339 matched concentrations in the fermentation medium of the wild type strain or the overexpression
340 mutant. When performing the preference tests with the supplemented medium pitted against blank
341 medium, attraction of the parasitoids was restored, especially when the medium was supplemented
342 with ethyl acetate (Fig. 3). When the supplemented media were tested against the media of the
343 wild type strain (Fig. 4A) or the overexpression mutant (Fig. 4B), no significant difference in
344 preference for either medium was observed, supporting the central role of these esters in the altered
345 attraction phenotype. When testing the individual esters at two concentrations resembling those in
346 the original attractive media, no statistically significant effects were observed (Fig. 5).

348

349

DISCUSSION

350 In this study, we have shown that *T. drosophilae* is attracted to the same volatile compounds to
351 which its host in the adult stage is attracted, particularly acetate esters. Parasitoids significantly
352 preferred the odour of the wildtype *S. cerevisiae* strain or its *ATF1* overexpressing mutant over the
353 blank medium in a Y-tube olfactometer. By contrast, deletion of the *ATF1* gene decreased
354 attraction of *T. drosophilae*, while simple addition of synthetic acetate esters to the fermentation
355 medium restored parasitoid attraction. Previous studies have shown that fruit flies in the family
356 Drosophilidae strongly respond to acetate esters to orient themselves towards suitable food or
357 oviposition sites. Ethyl acetate and isoamyl acetate have been found to attract *D. melanogaster*
358 (Christiaens et al., 2014). Isoamyl acetate is also responsible for attraction of the closely related

359 species *D. simulans*, but attraction seems largely dependent on the background chemical matrix
360 (Günther et al., 2015). Likewise, *D. suzukii* is strongly attracted to isobutyl acetate and isoamyl
361 acetate (Revadi et al., 2015; Scheidler et al., 2015). Moreover, neurobiological research has shown
362 that *Drosophila* antennae possess specific receptors for acetate esters, indicating that they have
363 evolved specific mechanisms to detect and respond to the fruity yeast esters (Vosshall et al., 2000;
364 Hallem & Carlson, 2006; Hallem et al., 2004). Notably, some plants have taken advantage of the
365 drosophilids' ability to detect acetate esters. For example, the black calla lily (*Arum palaestinum*)
366 has evolved to mimic yeast fermentation volatiles specifically by producing 2,3-butanediol acetate
367 and acetoin acetate to lure drosophilids for pollination (Stökl et al., 2010).

368 In addition to *T. drosophilidae* other fruit fly parasitoids have been shown to respond
369 positively to acetate esters, including the *Drosophila* larval parasitoid *Leptopilina heterotoma*
370 (Dicke et al., 1983) and *Biosteres longicaudatus*, a parasitoid of the Caribbean fruit fly
371 (*Anastrepha suspensa*) (Greany et al., 1977). More generally, previous studies have shown that
372 various insect species are attracted to acetate esters (Davis et al., 2013), suggesting that responding
373 to acetate esters may be a general trait in insects. This is further supported by studies that have
374 shown that receptors for acetate esters are widespread in insects (Galizia et al., 1999; Zhao &
375 McBride, 2020). For example, the dusky sap beetle *Carpophilus lugubris* is attracted to ethyl
376 acetate, amongst some other tested volatiles (Lin & Phelan, 1991), while Alm et al. (1985)
377 employed butyl acetate to attract *Glischrochilus* beetles. Likewise, the aphid parasitoid *Aphidius*
378 *ervi* was found to be attracted by the wild type *S. cerevisiae* strain used in this study (Y182) (Sobhy
379 et al., 2018).

380 Insect foraging driven by yeast volatiles may be influenced by the yeast species and the
381 basal growth medium as the precise composition of the VOC blends largely depends on the yeast

382 species and the precursors available (Dzialo et al., 2017; Gonzalez et al., 2019). Several yeast
383 species have been isolated from the body of *Drosophila* flies and their food and oviposition sites,
384 including members of *Candida*, *Hanseniaspora* and *Pichia* (Buser et al., 2014; Christiaens et al.,
385 2014; Hamby et al., 2012; Phaff & Knapp, 1956; Quan & Eisen, 2018). However, it has been found
386 that the vast majority of these yeasts produce aroma-active esters like ethyl acetate and isoamyl
387 acetate (Christiaens et al., 2014; Scheidler et al., 2015), and that fruit flies did not respond
388 differentially to the yeast species (Quan & Eisen, 2018). It has been hypothesized that these yeast
389 species employ the same biosynthetic pathway as *S. cerevisiae* for their active dispersal by the
390 fruit flies (Christiaens et al., 2014). However, acetate esters are not exclusively produced by
391 *Drosophila*-associated yeasts, they generally occur in yeast fermentations (Dzialo et al., 2017).
392 Furthermore, these volatile esters are produced by many plant species contributing to the
393 characteristic aroma of several fruits and flowers (Macku & Jennings, 1987; Shalit et al., 2003;
394 Schwab et al., 2008). This would make acetate esters unreliable as a signal, leading parasitoids to
395 many habitats lacking hosts. However, chemical stimuli can achieve more specificity in several
396 ways, e.g. through a specific concentration or a specific combination of compounds (in specific
397 concentrations and ratios) (Bruce et al., 2005; Goelen et al., 2021; Mumm & Hilker, 2005; Olson
398 et al., 2012; Takemoto & Takabayashi, 2015). In our tests, none of the individual compounds tested
399 could compete with the VOC blend of *S. cerevisiae*, suggesting that other yeast volatiles also
400 contribute to attraction of *T. drosophilae*. Further research should therefore focus on testing other
401 (concentrations and combinations of) fermentation products, or other volatile compounds
402 associated with the host habitat, in combination with acetate esters to fully understand the
403 attractivity of yeast odours for *T. drosophilae* or its foraging behaviour in general.

404 Altogether, our results show that *T. drosophilae* is attracted to the same volatile cues that
405 are exploited by the adult stage of its host. Whereas the mutualistic interaction between yeasts and
406 fruit flies has been well documented over the last few years, our results indicate that the same yeast
407 volatiles signaling appropriate resources for adult *Drosophila* flies may also give away the
408 presence of its offspring to parasitoids, potentially disrupting this mutualistic relation.

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REFERENCES

411 Agelopoulos, N. G., Dicke, M., & Posthumus, M. A. (1995). Role of volatile inforchemicals
412 emitted by feces of larvae in host-searching behavior of parasitoid *Cotesia rubecula*
413 (Hymenoptera: Braconidae): A behavioral and chemical study. *Journal of Chemical Ecology*,
414 *21*(11), 1789–1811. <https://doi.org/10.1007/BF02033677>

415 Alm, S. R., Hall, F. R., Ladd, T. L., & Williams, R. N. (1985). A chemical attractant for
416 *Glischrochilus quadrisignatus* (Coleoptera: Nitidulidae). *Journal of Economic Entomology*,
417 *78*(4), 839–843. <https://doi.org/10.1093/jee/78.4.839>

418 Altuzar, A., Montoya, P., & Rojas, J. C. (2004). Response of *Fopius arisanus* (Hymenoptera:
419 Braconidae) to fruit volatiles in a wind tunnel. *Florida Entomologist*, *87*(4), 616–618.
420 [https://doi.org/10.1653/0015-4040\(2004\)087\[0616:ROFAHB\]2.0.CO;2](https://doi.org/10.1653/0015-4040(2004)087[0616:ROFAHB]2.0.CO;2)

421 Arguello, J. R., Sellanes, C., Lou, Y. R., & Raguso, R. A. (2013). Can yeast (*S. cerevisiae*)
422 metabolic volatiles provide polymorphic signaling? *PLoS ONE*, *8*(8), e70219.
423 <https://doi.org/10.1371/journal.pone.0070219>

424 Becher, P. G., Flick, G., Rozpędowska, E., Alexandra, S., Hagman, A., Lebreton, S., Larsson, M.
425 C., Hansson, B. S., Piškur, J., Witzgall, P., & Bengtsson, M. (2012). Yeast, not fruit volatiles
426 mediate *Drosophila melanogaster* attraction, oviposition and development. *Functional*
427 *Ecology*, *26*, 822–828. <https://doi.org/10.1111/j.1365-2435.2012.02006.x>

428 Becher, P. G., Hagman, A., Verschut, V., Chakraborty, A., Rozpędowska, E., Lebreton, S.,
429 Bengtsson, M., Flick, G., Witzgall, P., & Piškur, J. (2018). Chemical signaling and insect
430 attraction is a conserved trait in yeasts. *Ecology and Evolution*, *8*(5), 2962–2974.
431 <https://doi.org/10.1002/ece3.3905>

432 Begon, M. (1982). Yeasts and *Drosophila*. In M. Ashburner, H. L. Carson, & Jr. J. N. Thompson
433 (Eds.), *The genetics and biology of Drosophila* (Vol. 3b, pp. 345–384). Academic Press,
434 London.

435 Bitas, V., Kim, H.-S., Bennett, J. W., & Kang, S. (2013). Sniffing on microbes: Diverse roles of
436 microbial volatile organic compounds in plant health. *Molecular Plant-Microbe Interactions*,
437 *26*(8), 835–843. <https://doi.org/10.1094/MPMI-10-12-0249-CR>

438 Bouletreau, M., & David, J. R. (1981). Sexually dimorphic response to host habitat toxicity in

439 *Drosophila* parasitic wasps. *Evolution*, 35(2), 395–399. <https://doi.org/10.2307/2407848>

440 Bruce, T. J. A., Wadhams, L. J., & Woodcock, C. M. (2005). Insect host location: a volatile
441 situation. *Trends in Plant Science*, 10(6), 269–274.
442 <https://doi.org/10.1016/j.tplants.2005.04.003>

443 Buser, C. C., Newcomb, R. D., Gaskett, A. C., & Goddard, M. R. (2014). Niche construction
444 initiates the evolution of mutualistic interactions. *Ecology Letters*, 17(10), 1257–1264.
445 <https://doi.org/10.1111/ele.12331>

446 Carrasco, M., Montoya, P., Cruz-lopez, L., & Rojas, J. C. (2005). Response of the fruit fly
447 parasitoid *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae) to mango fruit
448 volatiles. *Environmental Entomology*, 34(3), 576–583. [https://doi.org/10.1603/0046-225X-](https://doi.org/10.1603/0046-225X-34.3.576)
449 [34.3.576](https://doi.org/10.1603/0046-225X-34.3.576)

450 Carton, Y., Bouletreau, M., van Alphen, J. J. M., & van Lenteren, J. C. (1986). The *Drosophila*
451 parasitic wasps. In M. Ashburner, H. L. Carson, & Jr. J. N. Thompson (Eds.), *The genetics*
452 *and biology of Drosophila* (Vol. 3e, pp. 347-394). Academic Press, London.

453 Christiaens, J. F., Franco, L. M., Cools, T. L., De Meester, L., Michiels, J., Wenseleers, T., Hassan,
454 B. A., Yaksi, E., & Verstrepen, K. J. (2014). The fungal aroma gene *ATF1* promotes dispersal
455 of yeast cells through insect vectors. *Cell Reports*, 9(2), 425–432.
456 <https://doi.org/10.1016/j.celrep.2014.09.009>

457 Davis, T. S., Crippen, T. L., Hofstetter, R. W., & Tomberlin, J. K. (2013). Microbial volatile
458 emissions as insect semiochemicals. *Journal of Chemical Ecology*, 39(7), 840–859.
459 <https://doi.org/10.1007/s10886-013-0306-z>

460 Dicke, M., Van Lenteren, J. C., Boskamp, G. J. F., & Van Dongen-Van Leeuwen, E. (1984).
461 Chemical stimuli in host-habitat location by *Leptopilina heterotoma*
462 (Thomson)(Hymenoptera: Eucoilidae), a parasite of *Drosophila*. *Journal of Chemical*
463 *Ecology*, 10(5), 695–712. <https://doi.org/10.1007/BF00988537>

464 Dzialo, M. C., Park, R., Steensels, J., Lievens, B., & Verstrepen, K. J. (2017). Physiology, ecology
465 and industrial applications of aroma formation in yeast. *FEMS Microbiology Reviews*,
466 41(Supp_1), S95–S128. <https://doi.org/10.1093/femsre/fux031>

467 Eben, A., Benrey, B., Sivinski, J., & Aluja, M. (2000). Host species and host plant effects on
468 preference and performance of *Diachasmimorpha longicaudata* (Hymenoptera: Braconidae).
469 *Environmental Entomology*, 29(1), 87–94. <https://doi.org/10.1603/0046-225X-29.1.87>

470 Freese, E. B., Chu, M. I., & Freese, E. (1982). Initiation of yeast sporulation by partial carbon,
471 nitrogen, or phosphate deprivation. *Journal of Bacteriology*, 149(3), 840–851.

472 Gabarra, R., Riudavets, J., Rodríguez, G. A., Pujade-Villar, J., & Arnó, J. (2015). Prospects for
473 the biological control of *Drosophila suzukii*. *BioControl*, 60(3), 331–339.
474 <https://doi.org/10.1007/s10526-014-9646-z>

475 Galizia, C. G., Sachse, S., Rappert, A., & Menzel, R. (1999). The glomerular code for odor
476 representation is species specific in the honeybee *Apis mellifera*. *Nature Neuroscience*, 2(5),
477 473–478. <https://doi.org/10.1038/8144>

- 478 Goelen, T., Sobhy, I. S., Vanderaa, C., de Boer, J. G., Delvigne, F., Francis, F., Wäckers, F.,
479 Rediers, H., Verstrepen, K. J., Wenseleers, T., Jacquemyn, H., & Lievens, B. (2020).
480 Volatiles of bacteria associated with parasitoid habitats elicit distinct olfactory responses in
481 an aphid parasitoid and its hyperparasitoid. *Functional Ecology*, *34*(2), 507–520.
482 <https://doi.org/10.1111/1365-2435.13503>
- 483 Goelen, T., Vuts, J., Sobhy, I. S., Wäckers, F., Caulfield, J. C., Birkett, M. A., Rediers, H.,
484 Jacquemyn, H., & Lievens, B. (2020). Identification and application of bacterial volatiles to
485 attract a generalist aphid parasitoid: from laboratory to greenhouse assays. *Pest Management*
486 *Science*, *77*(2), 930–938. <https://doi.org/10.1002/ps.6102>
- 487 Gonzalez, M., Celis, A. M., Guevara-Suarez, M. I., Molina, J., & Carazzone, C. (2019). Yeast
488 smell like what they eat: analysis of volatile organic compounds of *Malassezia furfur* in
489 growth media supplemented with different lipids. *Molecules*, *24*(3), 419.
490 <https://doi.org/10.3390/molecules24030419>
- 491 Greany, P. D., Tumlinson, J. H., Chambers, D. L., & Boush, G. M. (1977). Chemically mediated
492 host finding by *Biosteres (Opus) longicaudatus*, a parasitoid of tephritid fruit fly larvae.
493 *Journal of Chemical Ecology*, *3*(2), 189–195. <https://doi.org/10.1007/BF00994145>
- 494 Günther, C. S., Goddard, M. R., Newcomb, R. D., & Buser, C. C. (2015). The context of chemical
495 communication driving a mutualism. *Journal of Chemical Ecology*, *41*(10), 929–936.
496 <https://doi.org/10.1007/s10886-015-0629-z>
- 497 Ha, E.-M., Lee, K.-A., Park, S. H., Kim, S.-H., Nam, H.-J., Lee, H.-Y., Kang, D., & Lee, W.-J.
498 (2009). Regulation of DUOX by the Gαq-phospholipase Cβ-Ca²⁺ pathway in *Drosophila* gut
499 immunity. *Developmental Cell*, *16*(3), 386–397.
500 <https://doi.org/10.1016/j.devcel.2008.12.015>
- 501 Hallem, E. A., Ho, M. G., & Carlson, J. R. (2004). The molecular basis of odor coding in the
502 *Drosophila* antenna. *Cell*, *117*(7), 965–979. <https://doi.org/10.1016/j.cell.2004.05.012>
- 503 Hallem, E. A., & Carlson, J. R. (2006). Coding of odors by a receptor repertoire. *Cell*, *125*(1),
504 143–160. <https://doi.org/10.1016/j.cell.2006.01.050>
- 505 Hamby, K. A., Hernández, A., Boundy-Mills, K., & Zalom, F. G. (2012). Associations of yeasts
506 with spotted-wing *Drosophila* (*Drosophila suzukii*; Diptera: Drosophilidae) in cherries and
507 raspberries. *Applied and Environmental Microbiology*, *78*(14), 4869–4873.
508 <https://doi.org/10.1128/AEM.00841-12>
- 509 Holighaus, G., & Rohlf, M. (2016). Fungal allelochemicals in insect pest management. *Applied*
510 *Microbiology and Biotechnology*, *100*, 5681–5689. <https://doi.org/10.1007/s00253-016-7573-x>
- 512 Jumean, Z., Jones, E., & Gries, G. (2009). Does aggregation behavior of codling moth larvae,
513 *Cydia pomonella*, increase the risk of parasitism by *Mastrus ridibundus*? *Biological Control*,
514 *49*(3), 254–258. <https://doi.org/10.1016/j.biocontrol.2009.03.003>
- 515 Leroy, P. D., Sabri, A., Verheggen, F. J., Francis, F., Thonart, P., & Haubruge, E. (2011). The
516 semiochemically mediated interactions between bacteria and insects. *Chemoecology*, *21*(3),
517 113–122. <https://doi.org/10.1007/s00049-011-0074-6>

- 518 Leyva, J. L., Browning, H. W., & Gilstrap, F. E. (1991). Effect of host fruit species, size, and color
519 on parasitization of *Anastrepha ludens* (Diptera: Tephritidae) by *Diachasmimorpha*
520 *longicaudata* (Hymenoptera: Braconidae). *Environmental Entomology*, 20(5), 1469–1474.
521 <https://doi.org/10.1093/ee/20.5.1469>
- 522 Lilly, M., Lambrechts, M. G., & Pretorius, I. S. (2000). Effect of increased yeast alcohol
523 acetyltransferase activity on flavor profiles of wine and distillates. *Applied and*
524 *Environmental Microbiology*, 66(2), 744–753. [https://doi.org/10.1128/AEM.66.2.744-](https://doi.org/10.1128/AEM.66.2.744-753.2000)
525 [753.2000](https://doi.org/10.1128/AEM.66.2.744-753.2000)
- 526 Lin, H., & Phelan, P. L. (1991). Identification of food volatiles attractive to dusky sap beetle,
527 *Carpophilus lugubris* (Coleoptera: Nitidulidae). *Journal of Chemical Ecology*, 17(6), 1273–
528 1286. <https://doi.org/10.1007/BF01402949>
- 529 Macku, C., & Jennings, W. G. (1987). Production of volatiles by ripening bananas. *Journal of*
530 *Agricultural and Food Chemistry*, 35(5), 845–848. <https://doi.org/10.1021/jf00077a049>
- 531 Madden, A. A., Epps, M. J., Fukami, T., Irwin, R. E., Sheppard, J., Sorger, D. M., & Dunn, R. R.
532 (2018). The ecology of insect–yeast relationships and its relevance to human industry.
533 *Proceedings of the Royal Society B: Biological Sciences*, 285(1875), 20172733.
534 <https://doi.org/10.1098/rspb.2017.2733>
- 535 Mazzetto, F., Marchetti, E., Amiresmaeili, N., Sacco, D., Francati, S., Jucker, C., Dindo, M. L.,
536 Lupi, D., & Tavella, L. (2016). *Drosophila* parasitoids in northern Italy and their potential to
537 attack the exotic pest *Drosophila suzukii*. *Journal of Pest Science*, 89(3), 837–850.
538 <https://doi.org/10.1007/s10340-016-0746-7>
- 539 Mumm, R., & Hilker, M. (2005). The significance of background odour for an egg parasitoid to
540 detect plants with host eggs. *Chemical Senses*, 30(4), 337–343.
541 <https://doi.org/10.1093/chemse/bji028>
- 542 Murgier, J., Everaerts, C., Farine, J.-P., & Ferveur, J.-F. (2019). Live yeast in juvenile diet induces
543 species-specific effects on *Drosophila* adult behaviour and fitness. *Scientific Reports*, 9(1),
544 8873. <https://doi.org/10.1038/s41598-019-45140-z>
- 545 Ogueta, M., Cibik, O., Eltrop, R., Schneider, A., & Scholz, H. (2010). The influence of Adh
546 function on ethanol preference and tolerance in adult *Drosophila melanogaster*. *Chemical*
547 *Senses*, 35(9), 813–822. <https://doi.org/10.1093/chemse/bjq084>
- 548 Oksanen, J., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., O'hara, R. B., Simpson, G.
549 L., Solymos, P., Stevens, M. H. H., & Wagner, H. (2013). Package ‘vegan.’ In *Community*
550 *ecology package* (Vol. 2, Issue 9, pp. 1–295).
- 551 Olson, D., Wäckers, F., & Haugen, J. (2012). Threshold detection of boar taint chemicals using
552 parasitic wasps. *Journal of Food Science*, 77(10), S356–S361. [https://doi.org/10.1111/j.1750-](https://doi.org/10.1111/j.1750-3841.2012.02883.x)
553 [3841.2012.02883.x](https://doi.org/10.1111/j.1750-3841.2012.02883.x)
- 554 Phaff, H. J., & Knapp, E. P. (1956). The taxonomy of yeasts found in exudates of certain trees and
555 other natural breeding sites of some species of *Drosophila*. *Antonie van Leeuwenhoek*, 22(1),
556 117–130. <https://doi.org/10.1007/BF02538319>
- 557 Phaff, H. J., & Starmer, W. T. (1987). Yeasts associated with plants, insects and soil. In A. H. Rose

558 & J. S. Harrison (Eds.), *The yeasts. Biology of yeasts* (Vol. 1, pp. 123–180). Academic Press,
559 New York.

560 Pozo, M. I., Bartlewicz, J., van Oystaeyen, A., Benavente, A., van Kemenade, G., Wäckers, F., &
561 Jacquemyn, H. (2018). Surviving in the absence of flowers: do nectar yeasts rely on
562 overwintering bumblebee queens to complete their annual life cycle? *FEMS Microbiology*
563 *Ecology*, *94*(12), fiy196. <https://doi.org/10.1093/femsec/fiy196>

564 Quan, A. S., & Eisen, M. B. (2018). The ecology of the *Drosophila*-yeast mutualism in wineries.
565 *PLOS ONE*, *13*(5), e0196440. <https://doi.org/10.1371/journal.pone.0196440>

566 R Core Team (2019). *R: A language and environment for statistical computing*. Vienna, Austria:
567 R Foundation for Statistical Computing. Retrieved from <https://www.R-project.org>.

568 Reuter, M., Bell, G., & Greig, D. (2007). Increased outbreeding in yeast in response to dispersal
569 by an insect vector. *Current Biology*, *17*(3), R81–R83.
570 <https://doi.org/10.1016/j.cub.2006.11.059>

571 Revadi, S. Vitagliano, S., Stacconi, M. V. R., Ramasamy, S., Mansourian, S., Carlin, S., Vrhovsek,
572 U., Becher, P. G., Mazzoni, V., Rota-Stabelli, O., Angeli, S., Dekker, T., & Anfora, G. (2015).
573 Olfactory responses of *Drosophila suzukii* femalesto host plant volatiles. *Physiological*
574 *Entomology*, *40*(1), 54–64. <https://doi.org/10.1111/phen.12088>

575 Scheidler, N. H., Liu, C., Hamby, K. A., Zalom, F. G., & Syed, Z. (2015). Volatile codes:
576 Correlation of olfactory signals and reception in *Drosophila*-yeast chemical communication.
577 *Scientific Reports*, *5*(1), 14059. <https://doi.org/10.1038/srep14059>

578 Schulz-Bohm, K., Martín-Sánchez, L., & Garbeva, P. (2017). Microbial volatiles: small molecules
579 with an important role in intra-and inter-kingdom interactions. *Frontiers in Microbiology*, *8*,
580 2484. <https://doi.org/10.3389/fmicb.2017.02484>

581 Schwab, W., Davidovich-Rikanati, R., & Lewinsohn, E. (2008). Biosynthesis of plant-derived
582 flavor compounds. *The Plant Journal*, *54*(4), 712–732. <https://doi.org/10.1111/j.1365-313X.2008.03446.x>

584 Shalit, M., Guterman, I., Volpin, H., Bar, E., Tamari, T., Menda, N., Adam, Z., Zamir, D.,
585 Vainstein, A., Weiss, D., Pichersky, E., & Lewinsohn, E. (2003). Volatile ester formation in
586 roses. Identification of an acetyl-coenzyme A. geraniol/citronellol acetyltransferase in
587 developing rose petals. *Plant Physiology*, *131*(4), 1868–1876.
588 <https://doi.org/10.1104/pp.102.018572>

589 Skorupa, D. A., Dervisefendic, A., Zwiener, J., & Pletcher, S. D. (2008). Dietary composition
590 specifies consumption, obesity, and lifespan in *Drosophila melanogaster*. *Aging Cell*, *7*(4),
591 478–490. <https://doi.org/10.1111/j.1474-9726.2008.00400.x>

592 Sobhy, I. S., Baets, D., Goelen, T., Herrera-Malaver, B., Bosmans, L., Van den Ende, W.,
593 Verstrepen, K. J., Wäckers, F., Jacquemyn, H., & Lievens, B. (2018). Sweet scents: Nectar
594 specialist yeasts enhance nectar attraction of a generalist aphid parasitoid without affecting
595 survival. *Frontiers in Plant Science*, *9*, 1009. <https://doi.org/10.3389/fpls.2018.01009>

596 Stefanini, I., Dapporto, L., Legras, J.-L., Calabretta, A., Di Paola, M., De Filippo, C., Viola, R.,
597 Capretti, P., Polsinelli, M., Turillazzi, S., & Cavalieri, D. (2012). Role of social wasps in

- 598 *Saccharomyces cerevisiae* ecology and evolution. *Proceedings of the National Academy of*
599 *Sciences*, 109(33), 13398–13403. <https://doi.org/10.1073/pnas.1208362109>
- 600 Stökl, J., Strutz, A., Dafni, A., Svatos, A., Doubsky, J., Knaden, M., Sachse, S., Hansson, B. S., &
601 Stensmyr, M. C. (2010). A deceptive pollination system targeting drosophilids through
602 olfactory mimicry of yeast. *Current Biology*, 20(20), 1846–1852.
603 <https://doi.org/10.1016/j.cub.2010.09.033>
- 604 Sullivan, B. T., Pettersson, E. M., Seltmann, K. C., & Berisford, C. W. (2000). Attraction of the
605 bark beetle parasitoid *Roptrocercus xylophagorum* (Hymenoptera: Pteromalidae) to host-
606 associated olfactory cues. *Environmental Entomology*, 29(6), 1138–1151.
607 <https://doi.org/10.1603/0046-225X-29.6.1138>
- 608 Takemoto, H., & Takabayashi, J. (2015). Parasitic wasps *Aphidius ervi* are more attracted to a
609 blend of host-induced plant volatiles than to the independent compounds. *Journal of*
610 *Chemical Ecology*, 41(9), 801–807. <https://doi.org/10.1007/s10886-015-0615-5>
- 611 Tilocca, B., Cao, A., & Migheli, Q. (2020). Scent of a killer: microbial volatilome and its role in
612 the biological control of plant pathogens. *Frontiers in Microbiology*, 11(41).
613 <https://doi.org/10.3389/fmicb.2020.00041>
- 614 Turlings, T. C. L., Wäckers, F. L., Vet, L. E. M., Lewis, W. J., & Tumlinson, J. H. (1993). Learning
615 of host-finding cues by hymenopterous parasitoids. In D. R. Papaj & A. C. Lewis (Eds.),
616 *Insect learning: Ecology and evolutionary perspectives* (pp. 51–78). Springer, Boston, MA.
617 https://doi.org/10.1007/978-1-4615-2814-2_3
- 618 Verstrepen, K. J., Van Laere, S. D. M., Vanderhaegen, B. M. P., Derdelinckx, G., Dufour, J.-P.,
619 Pretorius, I. S., Winderickx, J., Thevelein, J. M., & Delvaux, F. R. (2003). Expression levels
620 of the yeast alcohol acetyltransferase Genes *ATF1*, *Lg-ATF1*, and *ATF2* control the formation
621 of a broad range of volatile esters. *Applied and Environmental Microbiology*, 69(9), 5228–
622 5237. <https://doi.org/10.1128/AEM.69.9.5228-5237.2003>
- 623 Vet, L. E. M., Janse, C., van Achterberg, C., & van Alphen, J. J. M. (1984). Microhabitat location
624 and niche segregation in two sibling species of drosophilid parasitoids: *Asobara tabida* (Nees)
625 and *A. rufescens* (Foerster) (Braconidae: Alysiinae). *Oecologia*, 61(2), 182–188.
626 <https://doi.org/10.1007/BF00396757>
- 627 Vet, L. E. M., Lewis, W. J., & Cardé, R. T. (1995). Parasitoid foraging and learning. In R. T. Cardé
628 & W. J. Bell (Eds.), *Chemical ecology of insects 2* (pp. 65–101). Springer, Boston, MA.
629 https://doi.org/https://doi.org/10.1007/978-1-4615-1765-8_3
- 630 Vet, L. E. M., Hemerik, L., Visser, M. E., & Wäckers, F. L. (2002). Patch-use strategies of insect
631 parasitoids. In E. E. Lewis, J. F. Campbell, & M. V. K. Sukhdeo (Eds.), *The behavioural*
632 *ecology of parasites* (pp. 39–64). CABI Publishing, Wallingford.
- 633 Vosshall, L. B., Wong, A. M., & Axel, R. (2000). An olfactory sensory map in the fly brain. *Cell*,
634 102(2), 147–159. [https://doi.org/10.1016/S0092-8674\(00\)00021-0](https://doi.org/10.1016/S0092-8674(00)00021-0)
- 635 Walsh, D. B., Bolda, M. P., Goodhue, R. E., Dreves, A. J., Lee, J., Bruck, D. J., Walton, V. M.,
636 O’Neal, S. D., & Zalom, F. G. (2011). *Drosophila suzukii* (Diptera: Drosophilidae): Invasive
637 pest of ripening soft fruit expanding its geographic range and damage potential. *Journal of*

- 638 *Integrated Pest Management*, 2(1), G1–G7. <https://doi.org/10.1603/IPM10010>
- 639 Yi, C., Cai, P., Lin, J., Liu, X., Ao, G., Zhang, Q., Xia, H., Yang, J., & Ji, Q. (2020). Life history
640 and host preference of *Trichopria drosophilae* from southern China, one of the effective pupal
641 parasitoids on the *Drosophila* species. *Insects*, 11(2), 103.
642 <https://doi.org/10.3390/insects11020103>
- 643 Zhao, Z., & McBride, C. S. (2020). Evolution of olfactory circuits in insects. *Journal of*
644 *Comparative Physiology A*, 206(3), 353–367. <https://doi.org/10.1007/s00359-020-01399-6>
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646 TABLES

647 **Table 1.** Microbial volatile profiles (ppm)^{*} of the three yeast strains used in this study[†]

Compound [§]	N ^{o#}	Blank [§]	WT-Y182	DEL-KV3734	OE-KV3735	P value
Ethyl acetate	1	1.59 ± 0.01^a	28.16 ± 0.68^c	15.36 ± 0.86^b	100.16 ± 2.30^d	<0.001
Ethyl butyrate	2	ND ^a	0.23 ± 0.01 ^b	0.23 ± 0.01 ^b	0.22 ± 0.01 ^b	<0.001
Ethyl isobutyrate	3	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00	0.59
Ethyl-2-methylbutyrate	4	ND ^a	0.23 ± 0.06 ^b	0.15 ± 0.05 ^{ab}	0.21 ± 0.06 ^b	0.04
Ethyl isovalerate	5	0.01 ± 0.01	0.07 ± 0.07	ND	0.49 ± 0.49	0.49
Ethyl hexanoate	6	ND ^a	0.05 ± 0.00 ^b	0.05 ± 0.00 ^b	0.04 ± 0.00 ^b	<0.001
Ethyl octanoate	7	0.05 ± 0.00 ^a	0.10 ± 0.00 ^b	0.11 ± 0.00 ^b	0.11 ± 0.00 ^b	<0.001
Ethyl decanoate	8	0.02 ± 0.00 ^a	0.10 ± 0.01 ^b	0.12 ± 0.01 ^b	0.13 ± 0.01 ^b	<0.001
1-Propanol	9	0.66 ± 0.66 ^a	49.26 ± 1.09 ^b	53.76 ± 1.06 ^c	47.15 ± 0.78 ^b	<0.001
Propyl acetate	10	ND^a	0.01 ± 0.00^b	ND^a	0.01 ± 0.00^b	0.006
Isobutanol	11	ND ^a	80.66 ± 1.98 ^c	81.03 ± 1.54 ^c	69.94 ± 1.10 ^b	<0.001
Isobutyl acetate	12	0.01 ± 0.00^a	0.16 ± 0.01^b	0.03 ± 0.00^a	0.85 ± 0.05^c	<0.001
Isoamyl alcohol	13	ND ^a	128.24 ± 5.62 ^b	151.59 ± 2.76 ^c	117.93 ± 4.71 ^b	<0.001
Isoamyl acetate	14	0.30 ± 0.00^a	0.74 ± 0.02^b	0.36 ± 0.01^a	3.19 ± 0.22^c	<0.001
1-Hexanol	15	ND ^a	ND ^a	0.03 ± 0.00 ^b	ND ^a	<0.001
Hexyl acetate	16	ND^a	0.01 ± 0.00^b	0.01 ± 0.00^b	0.01 ± 0.00^b	<0.001
Phenylethyl alcohol	17	1.59 ± 0.48 ^a	13.26 ± 2.85 ^b	11.70 ± 0.44 ^b	13.17 ± 3.11 ^b	0.01
Phenylethyl acetate	18	ND^a	0.11 ± 0.00^b	0.00 ± 0.00^a	0.72 ± 0.08^c	<0.001

648 ^{*} Average of three biological replicates ± SEM. Values with different superscript letters in a row are
649 significantly different ($P < 0.05$). ND, not detected.

650 [†] Tested strains included the wild type *Saccharomyces cerevisiae* strain Y182 (WT-Y182), its *ATF1*
651 deletion mutant (DEL-KV3734) and its *ATF1* overexpression mutant (OE-KV3735).

652 [§] Acetate esters are displayed in bold.

653 [#] Numbers refer to the vectors shown in Fig. 1.

654 [§] Non-inoculated cultivation medium.

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663 **FIGURE CAPTIONS**

664 **Figure 1.** Principal component analysis (PCA) of the volatile profiles produced by the three
665 *Saccharomyces cerevisiae* strains investigated, including the wild type strain Y182 (WT-Y182),
666 the *ATF1* deletion mutant (DEL-KV3734) and the *ATF1* overexpression mutant (OE-KV3735),
667 and the non-inoculated cultivation medium (blank). The closer the dots together, the more similar
668 the VOC profiles. Vectors (red arrows) represent the loadings for each compound. The length of
669 the arrows approximates the variance of the variables, whereas the angles between them
670 approximate their correlations. Numbers refer to the different compounds measured: (1) ethyl
671 acetate; (2) ethyl butyrate; (3) ethyl isobutyrate; (4) ethyl-2-methylbutyrate; (5) ethyl isovalerate;
672 (6) ethyl hexanoate; (7) ethyl octanoate; (8) ethyl decanoate; (9) 1-propanol; (10) propyl acetate;
673 (11) isobutanol; (12) isobutyl acetate; (13) isoamyl alcohol; (14) isoamyl acetate; (15) 1-hexanol;
674 (16) hexyl acetate; (17) phenylethyl alcohol; and (18) phenylethyl acetate. All analyses were
675 performed on cell-free fermentation media (three biological replicates).

676

677 **Figure 2.** Olfactory response of adult *Trichopria drosophilae* females (tested in 12 cohorts of five
678 females) when given the choice between the odor of the non-inoculated cultivation medium (blank)
679 and one of the three *Saccharomyces cerevisiae* strains investigated. Tested yeast strains included
680 the wild type strain Y182 (WT-Y182), the *ATF1* deletion mutant (DEL-KV3734) and the *ATF1*
681 overexpression mutant (OE-KV3735). The used parasitoids were naïve (*i.e.* inexperienced to smell
682 and food). Non_responders were eliminated from statistical analysis. Error bars represent standard
683 error of the mean. Mean parasitoid responsiveness was 72.8%.

684

685 **Figure 3.** Olfactory response of adult *Trichopria drosophilae* females (tested in 12 cohorts of five
686 females) when given the choice between the odor of the non-inoculated cultivation medium (blank)
687 and the *Saccharomyces cerevisiae* *ATF1* deletion mutant (DEL-KV3734) fermentation medium
688 supplemented with one or more acetate esters at concentrations that matched the levels in the
689 medium of the wild type strain (WT-Y182) (A) and the *ATF1* overexpression mutant (OE-
690 KV3735) (B). Tested esters included ethyl acetate (EA), isoamyl acetate (IA) and phenylethyl
691 acetate (PA). The used parasitoids were naïve (*i.e.* inexperienced to smell and food). Non-
692 responders were eliminated from statistical analysis. Error bars represent standard error of the
693 mean. Mean parasitoid responsiveness was 71.7%.

694

695 **Figure 4.** Olfactory response of adult *Trichopria drosophilae* females (tested in 12 cohorts of five
696 females) when given the choice between the odor of the wild type *Saccharomyces cerevisiae* strain
697 (WT-Y182) or the *ATF1* overexpression mutant (OE-KV3735) and the *ATF1* deletion mutant
698 (DEL-KV3734) fermentation medium supplemented with one or more acetate esters at
699 concentrations that matched the levels in the medium of the wild type strain (A) or the *ATF1*
700 overexpression mutant (B). Tested esters included ethyl acetate (EA), isoamyl acetate (IA) and
701 phenylethyl acetate (PA). The used parasitoids were naïve (*i.e.* inexperienced to smell and food).
702 Non-responders were eliminated from statistical analysis. Error bars represent standard error of
703 the mean. Mean parasitoid responsiveness was 69.2%.

704

705 **Figure 5.** Olfactory response of adult *Trichopria drosophilae* females (tested in 12 cohorts of five
706 females) when given the choice between two different concentrations of ethyl acetate (0.1 ppm
707 and 1 ppm), isoamyl acetate (0.001 ppm and 0.01 ppm) and phenylethyl acetate (0.001 ppm and

708 0.01 ppm) dissolved in diethyl ether and a diethyl ether blank in a Y-tube olfactometer bioassay.
709 The used parasitoids were naïve (*i.e.* inexperienced to smell and food). Non-responders were
710 eliminated from statistical analysis. Error bars represent standard error of the mean. Mean
711 parasitoid responsiveness was 67.4%.