The role of specific tomato volatiles in tomato-whitefly interaction

Bleeker, P. M.; Diergaard, P. J.; Ament, K.; Guerra, J.; Weidner, M.; Schütz, S.; de Both, M. T. J.; Haring, M. A.; Schuurink, R. C.

Published in:
Plant Physiology

DOI:
10.1104/pp.109.142661

Citation for published version (APA):
The Role of Specific Tomato Volatiles in Tomato-Whitefly Interaction\textsuperscript{1[W][OA]}

Petra M. Bleeker, Paul J. Diergaarde, Kai Ament, José Guerra, Monique Weidner, Stefan Schütz, Michiel T.J. de Both, Michel A. Haring, and Robert C. Schuurink\textsuperscript{*}

Keygene, 6700 AE Wageningen, The Netherlands (P.M.B., P.J.D., J.G., M.T.J.B.); University of Amsterdam, Swammerdam Institute for Life Sciences, Department of Plant Physiology, 1098 XH Amsterdam, The Netherlands (P.M.B., K.A., M.A.H., R.C.S.); and University of Göttingen, Department of Forest Zoology and Forest Conservation, 37077 Goettingen, Germany (M.W., S.S.)

\textit{Bemisia tabaci} (whitefly) infestations and the subsequent transfer of viruses are the cause of severe losses in crop production and horticultural practice. To improve biological control of \textit{B. tabaci}, we investigated repellent properties of plant-produced semiochemicals. The mix of headspace volatiles, collected from naturally repellent wild tomato accessions, influenced \textit{B. tabaci} initial choice behavior, indicating a role for plant semiochemicals in locating host plants. A collection of wild tomato accessions and introgression lines (\textit{Solanum pennellii} LA716 × \textit{Solanum lycopersicum} 'Moneyberg') were extensively screened for attractiveness to \textit{B. tabaci}, and their headspace profiles were determined by means of gas chromatography-mass spectrometry. Correlation analysis revealed that several terpenoids were putatively involved in tomato-whitefly interactions. Several of these candidate compounds conferred repellence to otherwise attractive tomato plants when applied to the plant's branches on paper cards. The sesquiterpenes zingiberene and curcumene and the monoterpenes \textit{p}-cymene, \textit{a}-terpinene, and \textit{\alpha}-phellandrene had the strongest effects in free-choice bioassays. These terpenes also elicited a response of receptors on the insect’s antennae as determined by electroantennography. Conversely, the monoterpene \textit{\beta}-myrcene showed no activity in both assays. \textit{B. tabaci} apparently uses, besides visual cues, specific plant volatile cues for the initial selection of a host. Altering whitefly choice behavior by manipulation of the terpenoid composition of the host headspace may therefore be feasible.

During the last decades, a worldwide spread of the pest insects \textit{Bemisia tabaci} (Gennadius) and greenhouse whitefly (\textit{Trialeurodes vaporariorum}) has led to local devastation of vegetable and ornamental crops, resulting in large economic losses. The damage whiteflies cause by their feeding behavior, such as affected biochemistry and development (for review, see Inbar and Gerling, 2008), is far exceeded by the secondary, indirect crop losses due to virus transmission. Specifically, \textit{B. tabaci} outbreaks are associated with the emergence of viruses for which they serve as vectors (Polston and Anderson, 1997). \textit{B. tabaci} is capable of transmitting >100 different virus species of which the majority belong to the genus \textit{Begomovirus}, such as \textit{Tomato yellow leaf curl virus}, \textit{Tomato mottle virus} (Jones, 2003), and \textit{African cassava mosaic virus} (Maruthi et al., 2001). Damage caused by virus infection ranges from mild symptoms, such as leaf discolorations, to overall yield reduction, severe fruit necrosis, flower and fruit abortions, and plant death. Viral diseases are particularly severe since no chemical control is available and good sources of virus resistance for interspecific crossing are not always available (Maruthi et al., 2003). To date, only a limited number of virus resistance genes have been identified, and due to high mutation rates, viruses rapidly evolve (Drake and Holland, 1999; García-Andrés et al., 2006) and break monogenic resistances. Herbivores, such as whiteflies and thrips, can apparently benefit from transmitting viruses (Medeiros et al., 2004; Jiu et al., 2007; Belliure et al., 2008).

\textit{B. tabaci} was originally restricted to subtropical regions and greenhouses. However, the new and extremely invasive \textit{B} and \textit{Q} biotypes have the ability to rapidly adapt to more temperate zones and new host species (Jones, 2003; Wan et al., 2008). To date, the main control strategy for many crops is the application of insecticides, though effective spraying is complicated because of the insect’s preference for the abaxial side of the leaf (Simmons, 1994). Moreover, \textit{B. tabaci} is difficult to control chemically due to emerging resistance to active ingredients (Horowitz et al., 2005). A new biological control agent, the phytoseiid predator \textit{Typhlodromips swirskii}, has only been successful on plants without trichomes in closed greenhouses (Nomikou et al., 2002). The root-knot nematode resis-
tance gene Mi1.2, which confers partial resistance to B. tabaci (Nombela et al., 2003), is widely used in modern tomato (Solanum spp.) varieties but is not sufficient to provide adequate protection against whitefly infestations.

During insect host selection, orientation, and landing, both visual and olfactory cues play a predominant role (Visser, 1988). Color is an important factor in host-plant selection, and it was shown that B. tabaci reacts to blue-UV and yellow wavelengths (Van Lenteren and Noldus, 1990). The olfactory stimuli associated with the host plant initiate host targeting, whereas visual cues improve the accuracy of landing. In the initial phase of host targeting, olfaction may cause a positive chemotactic response, i.e. a flight up an odor gradient. Plant odor specificity might be achieved by a particular ratio of constituent volatiles (Bruce et al., 2005a).

In the case of whiteflies, the role of olfaction in attraction or repellence has not received much prior attention. After host contact, B. tabaci evaluates host plant quality by labial dabbing and probing using piercing mouthparts. By probing, persistent viruses are transmitted via the insects’ salivary glands and mouthparts (Ghanim et al., 1998; Rosell et al., 1999). Therefore, to avoid virus transmission by B. tabaci, probing should be prevented.

Volatile organic compounds released by plants can act as semiochemicals. They play an important role in enabling insects to recognize host plants from a distance (Schütz et al., 1997; Bruce et al., 2005a) or in attracting predators and parasitoids upon herbivory (De Moraes et al., 1998; Van Poecke and Dicke, 2002; Kappers et al., 2005). Moreover, they can play a role in the direct defense against herbivores and pathogens (Kessler and Baldwin, 2001; Shiojiri et al., 2006). A large number of different plant volatiles, with numerous ecological roles, have been identified so far (Sacchetti and Poulter, 1997; Pichersky et al., 2006). The largest class of plant volatiles is derived from the isoprenoid or terpenoid pathway. Solanaceous plants, like tomato, often make use of these terpenes for the defense against herbivores (Snyder et al., 1993; Kennedy, 2003). Some terpenes have been shown to exhibit repellent properties to insects (Peterson et al., 2002; Birkett et al., 2004; Terry et al., 2007). These plant-produced semiochemicals can potentially be used as insect repellents of natural origin, thus providing an alternative to the use of pesticides (Peterson and Coats, 2001). Engineering terpene emission to make crop plants more attractive to herbivore enemies has already been shown to be feasible (Degenhardt et al., 2003; Kappers et al., 2005; Schnee et al., 2006).

The aim of this study is to identify the role of plant volatiles in the B. tabaci-tomato host interaction and to identify the terpenes that cause repellence of a selection of wild tomato accessions. The potential of several terpenes as repellent olfactory cues in B. tabaci host-preference behavior has been assessed in behavioral studies and through electroantennography (EAG).

### RESULTS

**Characterization of B. tabaci Populations**

Morphologically indistinguishable B. tabaci populations are known to exhibit large variations in biological traits as well as a distinct genetic variation. B. tabaci populations were collected from crop production sites all over the world, and the amplified fragment length polymorphism (AFLP) technique was used to investigate the extent and nature of intraspecific variability of the assorted B. tabaci populations.

Genetic diversity assessment of the various populations revealed three distinct clusters, which appear to be geographically correlated (Supplemental Fig. S1) and could be identified as biotype Q, biotype B, and an undetermined (U) biotype using biotype-specific PCR markers (Khasdan et al., 2005). Apparently, parts of Asia are dominated by biotype U and parts of Southern Europe by biotype Q. Biotype B dominates the greenhouses of several countries spread around the world. Genetic variation was not correlated to the seven crop species from which the B. tabaci populations were collected (data not shown), as expected for a generalist herbivore.

**Tomato Semiochemical Cues and B. tabaci Preference Behavior**

The relative attraction of B. tabaci to the accessions of the tomato collection, containing 16 wild and five cultivated tomatoes, was determined in free-choice bioassays with B. tabaci. In these bioassays, the number of flies per plant was counted 10 min after release in the center of the arena. Examination of host-preference behavior of two selected biotype populations (B and Q) revealed no differential preference behavior of these whiteflies in free-choice bioassays with cultivated and wild tomato (Fig. 1A; P > 0.5). Therefore, it was decided to use the Q biotype (Almería B) population in all further assays.

Prior to starting large-scale bioassays, it was established that B. tabaci preference behavior is indeed influenced by the volatiles in the headspace of the tomato plants. Preference assays were done with four different Solanum lycopersicum cultivars of the same age, height, shape, and color. Afterward, the experiment was repeated with the same plants now individually placed under a mesh cover (Supplemental Fig. S2) to conceal the shape and color of the plant so that whiteflies could make a choice based on the volatiles they detect. Even though fewer whiteflies were recaptured in the absence of visual cues, the relative distribution of whiteflies over tomatoes with different attraction did not change (P > 0.5) compared to that obtained with exposed plants (Fig. 1B). The presence of the Mi1.2 gene in two of the cultivated tomatoes (Motelle and Mogeor) had no influence on the choice of the whiteflies in our experimental setup.

Sequential stepwise bioassays revealed a clear preference of the whiteflies for cultivated tomato plants.
over the wild tomato accessions. *Solanum pennellii* LA2560 and *Solanum habrochaites* PI127826 ranked as least preferred, whereas *Solanum peruvianum* LA1708 was only slightly less attractive than the cultivated tomato plants as indicated by the classification in seven preference groups (Table I). Next, we determined whether the collected headspace volatiles of the two least preferred tomatoes ( *S. pennellii* LA2560 and *S. habrochaites* PI127826) could reduce the attractiveness of the cultivated tomato ( *S. lycopersicum* ‘Money-maker’). The headspace volatiles collected over 24 h were applied to a *S. lycopersicum* ‘Money-maker’ plant on 10 filter paper cards distributed over the entire plant (for concentrations, see Table I). Free-choice bioassays were performed with four plants, of which one received wild tomato volatiles. In this setup, the cultivated tomato with the headspace volatiles of LA2560 or PI127826 attracted up to 60% less whiteflies (Fig. 2, A and B, respectively). The carrier of the headspace volatiles, pentane-diethylether, alone did not affect the choice of *B. tabaci* (Fig. 2).

**Determining Headspace Components as Cues for Repellence**

In addition to bioassays, a headspace volatile fingerprint for each tomato plant of our collection was assembled using gas chromatography-mass spectrom-

---

### Table 1. Wild tomato accessions ( *S. pennellii*, *S. habrochaites*, and *S. peruvianum*) and cultivated tomato lines ( *S. lycopersicum*) ranked based on relative preference of *B. tabaci*

<table>
<thead>
<tr>
<th>Tomato</th>
<th>Accession</th>
<th>Ranking</th>
<th>β-Myrcene</th>
<th>p-Cymene</th>
<th>γ-Terpinene</th>
<th>Curcumene</th>
<th>Zingiberene</th>
<th>Caryophyllene</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. pennellii</em></td>
<td>LA716</td>
<td>2</td>
<td>–</td>
<td>0.34 ± 0.13</td>
<td>4.01 ± 1.71</td>
<td>10.83 ± 8.29</td>
<td>68.5 ± 58.9</td>
<td>0.55 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>LA1340</td>
<td>2</td>
<td>1.46 ± 0.45</td>
<td>0.35 ± 0.11</td>
<td>2.49 ± 0.96</td>
<td>4.46 ± 4.35</td>
<td>6.56 ± 6.56</td>
<td>2.01 ± 0.82</td>
</tr>
<tr>
<td></td>
<td>LA2560</td>
<td>3</td>
<td>1.36 ± 0.61</td>
<td>0.47 ± 0.18</td>
<td>5.88 ± 2.50</td>
<td>3.60 ± 4.30</td>
<td>8.44 ± 4.36</td>
<td>3.06 ± 1.50</td>
</tr>
<tr>
<td><em>S. habrochaites</em> (i. typicum)</td>
<td>PI127826</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>0.24 ± 0.24</td>
<td>282.4 ± 116.2</td>
<td>521.0 ± 323.6</td>
<td>0.28 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>PI127827</td>
<td>3</td>
<td>0.01 ± 0.01</td>
<td>0.03 ± 0.03</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.34 ± 0.21</td>
</tr>
<tr>
<td></td>
<td>LA1353</td>
<td>3</td>
<td>0.20 ± 0.12</td>
<td>0.01 ± 0.01</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2.56 ± 0.84</td>
</tr>
<tr>
<td><em>S. habrochaites</em> (i. glabratum)</td>
<td>PI126449</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>8.34 ± 2.61</td>
</tr>
<tr>
<td></td>
<td>PI134417</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>13.41 ± 5.98</td>
</tr>
<tr>
<td></td>
<td>PI134418</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.08 ± 1.10</td>
</tr>
<tr>
<td></td>
<td>PI251304</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.21 ± 0.21</td>
<td>–</td>
<td>7.23 ± 2.81</td>
</tr>
<tr>
<td></td>
<td>IV701631</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3.35 ± 3.21</td>
<td>–</td>
<td>7.27 ± 6.31</td>
</tr>
<tr>
<td></td>
<td>LA407</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>0.96 ± 0.96</td>
<td>–</td>
<td>–</td>
<td>3.64 ± 0.92</td>
</tr>
<tr>
<td></td>
<td>GI1560</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>11.1 ± 6.6</td>
<td>3.76 ± 3.76</td>
<td>3.48 ± 0.57</td>
</tr>
<tr>
<td><em>S. peruvianum</em></td>
<td>LA1840</td>
<td>5</td>
<td>0.02 ± 0.02</td>
<td>0.01 ± 0.01</td>
<td>0.05 ± 0.05</td>
<td>0.08 ± 0.05</td>
<td>0.88 ± 0.88</td>
<td>0.12 ± 0.05</td>
</tr>
<tr>
<td><em>S. lycopersicum</em></td>
<td>LA1708</td>
<td>5</td>
<td>0.09 ± 0.09</td>
<td>0.07 ± 0.03</td>
<td>1.13 ± 0.68</td>
<td>0.54 ± 0.54</td>
<td>–</td>
<td>2.88 ± 0.86</td>
</tr>
<tr>
<td></td>
<td>Motelle</td>
<td>6</td>
<td>0.08 ± 0.06</td>
<td>0.02 ± 0.01</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.54 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>Moneymaker</td>
<td>7</td>
<td>0.07 ± 0.07</td>
<td>0.01 ± 0.01</td>
<td>0.07 ± 0.07</td>
<td>0.11 ± 0.11</td>
<td>–</td>
<td>3.35 ± 2.41</td>
</tr>
<tr>
<td></td>
<td>Pitenza</td>
<td>6</td>
<td>0.17 ± 0.10</td>
<td>0.07 ± 0.04</td>
<td>0.07 ± 0.07</td>
<td>–</td>
<td>–</td>
<td>1.11 ± 0.21</td>
</tr>
</tbody>
</table>

---

**Figure 1.** Relative preference (as percentage recaptured *B. tabaci*, *n = 200*) for different tomato varieties. A, Results for genetically different *B. tabaci* populations; biotype Q (gray bars) and biotype B (black bars) on *S. lycopersicum* ‘Money-maker’ (MM), *S. habrochaites* GI1560, *S. habrochaites* LA1777, and *S. pennellii* LA2560. B, Results for *B. tabaci* biotype Q in the presence (gray bars) and absence (black bars) of visual cues in a setup with four *S. lycopersicum* plants: cv Motelle (containing *Mi1.2*), cv Monalbo, cv Moneymaker (containing *Mi1.2*), and cv Pitenza. Bars represent the means of three experiments (±SEM). Significant differences (*P < 0.05*) are indicated by different letters.
and the introgression lines (b) penes were detected in the headspaces of the parents. Moneyberg parent was determined. Seven monoterpenes from S. pennellii (PI127826) were analyzed for the production of green leaf volatiles (GLVs) by proton transfer reaction-mass spectrometry (Steeghs et al., 2006). Significant amounts of GLVs could only be detected after wounding the tomato plants (data not shown), ruling out the involvement of GLVs in B. tabaci host location.

Selected Semiochemicals and B. tabaci Behavior

To confirm the correlation between the seven candidate semiochemicals and B. tabaci behavior, host preference was assayed in bioassays with pure components. The selected pure volatile chemical(s) were administered on paper cards to Moneymaker plants (as described above). In the absence of added volatiles, the percentage of recaptured B. tabaci on each of the four tomato Moneymaker plants did not deviate significantly from the expected 25% (data not shown). However, when 10 μg p-cymene was spotted on a filter paper and added to one of the plants, this plant became significantly (P < 0.001; Table III) less attractive to the whiteflies compared to the control plants. The percentage of whiteflies visiting the plant with p-cymene decreased with 44% on average, whereas the control plants harbored increased numbers of B. tabaci, as expected (Fig. 3A). Addition of 10 μg β-myrcene on the other hand did not influence whitefly behavior (Fig. 3C). Application of 10 μg γ-terpinene to the Moneymaker plants appeared to reduce attractiveness, but the difference was not significant (Fig. 3B; Table III). To assess whether a blend of these three components would yield a greater effect than p-cymene alone, a mixture of p-cymene:γ-terpinene:β-myrcene in the same ratio as found in accession LA2560 (1:12:3 [v/v]) was tested. This resulted in reduced attractiveness for whiteflies with 45% on average (Fig. 3D). The putative repellent semiochemicals α-phellandrene and α-terpinene, both monoterpenes that were identified with the introgression line

---

**Figure 2.** Headspace volatiles from S. pennellii (A) and S. habrochaites (B) can repel whiteflies. Treatment effect of added wild tomato headspace volatiles in a setup of four S. lycopersicum ‘Moneymaker’ plants (expressed as percentage of untreated setup, n = 200) on B. tabaci biotype Q choice behavior. Empty, Empty carriers; pe, carriers containing pentane:diethylether; pennellii, carriers containing total headspace (collected over 24 h) of S. pennellii (LA2560); habrochaites, carriers containing total headspace (collected over 24 h) of S. habrochaites f. typicum (PI127826). Bars present averages of three experiments (±SE). Level of significance: *, P < 0.05; **, P < 0.01.
analyses, significantly decreased tomato attractiveness for whiteflies (Fig. 3, E and F; Table II). Finally, both sesquiterpenes that were tested, the *S. habrochaites*-derived zingiberene as well as its hydrogenation product curcumene, clearly reduced attractiveness (Fig. 3, G and H).

**DISCUSSION**

In this article, two functional metabolomic approaches led to the identification of several volatile mono- and sesquiterpenes from tomato that influence the whiteflies’ choice for this host. The addition of some of these terpenes to the headspace of an otherwise attractive, cultivated tomato plant significantly reduced the number of whitefly visitations or, in other words, made the plant less preferred. Based on these observations, i.e. host selection based on odor cues instead of visual cues, together with a specific antennal response to certain terpenes, we propose a significant role for plants volatiles in the choice behavior of whiteflies.

**Whiteflies Use Volatile Cues When Choosing a Host**

The AFLP result presented in Supplemental Figure S1 confirms the previously reported genetic genetic variation between whitefly populations (Frohlich et al., 1999). The invasive biotype B was even considered sufficiently different to be described as a new species (*Bemisia argentifolii* Bellows and Perring; Perring et al., 1993; Bellows et al., 1994), despite the morphological similarity to the indigenous biotype A. These distinct biotypes exhibit differential potential for virus transmission (Perring et al., 1993; Bedford et al., 1994). Interestingly, the B and Q biotype strains we tested preferred the same host in the choice assays (Fig. 1A), indicating some conservation of volatile perception and subsequent behavior.

Choice assays with tomato plants under a mesh cover indicated that whiteflies still make the same perception and subsequent behavior.

**Table II. Selection of introgression lines and their parents *S. lycopersicum* ‘Moneyberg’ and *S. pennellii* accession LA716 ranked based on relative preference of B. tabaci**

<table>
<thead>
<tr>
<th>Line</th>
<th>Ranking</th>
<th>β-Myrcene</th>
<th>2-Carene</th>
<th>α-Phellandrene</th>
<th>α-Terpine</th>
<th>p-Cymene</th>
<th>β-Phellandrene</th>
<th>γ-Terpine</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA716</td>
<td>1</td>
<td>2.15 ± 2.15</td>
<td>1.86 ± 1.86</td>
<td>4.78 ± 1.38</td>
<td>0.97 ± 0.97</td>
<td>1.63 ± 0.77</td>
<td>0.08 ± 0.08</td>
<td>2.38 ± 2.38</td>
<td>0.195 (ns)</td>
</tr>
<tr>
<td>173</td>
<td>2</td>
<td>9.18 ± 1.19</td>
<td>2.22 ± 0.71</td>
<td>0.60 ± 0.24</td>
<td>0.35 ± 0.14</td>
<td>0.17 ± 0.06</td>
<td>17.01 ± 7.64</td>
<td>0.01 ± 0.01</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>231</td>
<td>2</td>
<td>18.54 ± 2.78</td>
<td>4.08 ± 1.17</td>
<td>0.99 ± 0.23</td>
<td>0.58 ± 0.11</td>
<td>0.33 ± 0.15</td>
<td>37.55 ± 10.73</td>
<td>0.43 ± 0.26</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>576</td>
<td>2</td>
<td>16.22 ± 3.80</td>
<td>2.37 ± 1.73</td>
<td>0.50 ± 0.21</td>
<td>0.40 ± 0.33</td>
<td>0.11 ± 0.05</td>
<td>23.81 ± 13.59</td>
<td>0.08 ± 0.08</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>1126</td>
<td>2</td>
<td>9.03 ± 1.44</td>
<td>0.72 ± 0.13</td>
<td>0.24 ± 0.10</td>
<td>0.03 ± 0.03</td>
<td>0.05 ± 0.01</td>
<td>4.96 ± 0.85</td>
<td>0.001 (ns)</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>1201</td>
<td>2</td>
<td>22.48 ± 11.91</td>
<td>4.85 ± 3.20</td>
<td>1.04 ± 0.59</td>
<td>0.99 ± 0.72</td>
<td>0.16 ± 0.10</td>
<td>14.42 ± 7.06</td>
<td>0.17 ± 0.17</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>373</td>
<td>3</td>
<td>24.38 ± 15.15</td>
<td>1.29 ± 0.95</td>
<td>0.83 ± 0.72</td>
<td>0.18 ± 0.18</td>
<td>0.15 ± 0.12</td>
<td>6.49 ± 3.80</td>
<td>0.07 ± 0.07</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>981</td>
<td>3</td>
<td>13.27 ± 3.25</td>
<td>1.72 ± 1.01</td>
<td>0.42 ± 0.18</td>
<td>0.06 ± 0.04</td>
<td>0.16 ± 0.10</td>
<td>13.64 ± 9.37</td>
<td>0.001 (ns)</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>1007</td>
<td>3</td>
<td>20.96 ± 8.86</td>
<td>3.98 ± 1.98</td>
<td>0.93 ± 0.45</td>
<td>0.80 ± 0.46</td>
<td>0.19 ± 0.11</td>
<td>40.95 ± 21.57</td>
<td>0.11 ± 0.11</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>1036</td>
<td>3</td>
<td>12.79 ± 2.65</td>
<td>2.78 ± 1.38</td>
<td>0.32 ± 0.16</td>
<td>0.17 ± 0.17</td>
<td>0.17 ± 0.07</td>
<td>24.58 ± 11.53</td>
<td>0.04 ± 0.04</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>1074</td>
<td>4</td>
<td>19.09 ± 3.45</td>
<td>1.45 ± 0.30</td>
<td>0.69 ± 0.33</td>
<td>0.27 ± 0.02</td>
<td>0.14 ± 0.03</td>
<td>10.46 ± 1.61</td>
<td>0.04 ± 0.04</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>MB</td>
<td>5</td>
<td>5.43 ± 0.48</td>
<td>0.35 ± 0.06</td>
<td>0.0</td>
<td>0.0</td>
<td>0.02 ± 0.00</td>
<td>2.60 ± 0.33</td>
<td>0.001 (ns)</td>
<td>0.001 (ns)</td>
</tr>
<tr>
<td>P value</td>
<td></td>
<td>0.195 (ns)</td>
<td>0.140 (ns)</td>
<td>0.001</td>
<td>0.003</td>
<td>0.009</td>
<td>0.199 (ns)</td>
<td>0.357 (ns)</td>
<td></td>
</tr>
</tbody>
</table>

**Table III. Bioactivity of seven candidate semiochemicals from wild tomato accessions in choice bioassays (n = 8) and electroantennographic responses (µV plus scatter, n ≥ 5) of B. tabaci antennae (10–3 dilution in paraffin oil)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Terpenoid</th>
<th>Repellent Effect</th>
<th>Antennal Response in µV (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. pennellii</em></td>
<td>p-Cymene</td>
<td>P &lt; 0.001</td>
<td>24 (6–65)</td>
</tr>
<tr>
<td></td>
<td>β-Myrcene</td>
<td>P = 0.479</td>
<td>nr</td>
</tr>
<tr>
<td></td>
<td>γ-Terpine</td>
<td>P = 0.102</td>
<td>19 (5–36)</td>
</tr>
<tr>
<td></td>
<td>α-Terpine</td>
<td>P = 0.014</td>
<td>41 (31–126)</td>
</tr>
<tr>
<td></td>
<td>α-Phellandrene</td>
<td>P = 0.030</td>
<td>22 (0–78)</td>
</tr>
<tr>
<td><em>S. habrochaites</em></td>
<td>Zingiberene</td>
<td>P &lt; 0.001</td>
<td>23 (0–53)</td>
</tr>
<tr>
<td></td>
<td>Curcumene</td>
<td>P &lt; 0.001</td>
<td>50 (8–148)</td>
</tr>
</tbody>
</table>
Specific tomato volatile compounds can repel whiteflies. Effect of one volatile compound (or mix) added to one plant in a setup of four S. lycopersicum ‘Moneymaker’ plants (expressed as percentage of control setup, n = 200) on B. tabaci biotype Q choice behavior. Addition of 10 μg: p-cymene (A), γ-terpinene (B), β-myrcene (C), a mix of p-cymene, γ-terpinene, and β-myrcene (D), α-terpinene (E), α-phellandrene (F), zingiberene (G), and curcumene (H). Bars represent averaged values of eight experiments (±s.e) nt, Plants in setup to which no volatiles were added. Level of significance: *, P < 0.05; ***, P < 0.001.
the plants were covered, indicating that locating hosts effectively requires multimodal sensory signals, including visual cues.

Tomato Volatile Semiochemicals Can Influence Whitefly Choice Behavior

From previous studies it was known that the wild tomatoes S. pennellii and S. habrochaites (former Lycopersicon hirsutum) are less preferred by B. tabaci than cultivated tomato varieties, which was attributed to the production of volatiles by their glandular trichomes (Simmons and Gurr, 2005). Targeted approaches showed that undecanone, a fatty acid derivative (Fridman et al., 2005), and the sesquiterpene zingiberene (Antionious and Kochhar, 2003), both produced in the trichomes, were toxic to whiteflies (Freitas et al., 2002; Antonious et al., 2005). We decided to investigate the influence of the tomato headspace volatiles on the initial choice behavior of the whiteflies using short-choice assays of 10 min. In this way, the repellent effects of the headspace volatiles could be separated from gustatory cues after host contact. B. tabaci exhibited a clear preference for cultivated tomato varieties over wild tomatoes (Table I). It is known that airborne semiochemicals can promote or deter interactions between plants and herbivorous insects (reviewed in Bruce et al., 2005a). We showed that the addition of the mixture of volatile compounds present in the headspace of the two least preferred tomato accessions (LA2560 and PI127826) to an otherwise attractive cultivated tomato plant significantly reduced whitefly visitations (Fig. 2), showing that manipulation of olfactory cues can in fact alter the attractiveness of a host plant for B. tabaci.

Our untargeted approach of correlating the headspace profiles of 21 different tomato lines with their relative attractiveness revealed only terpenes as putative semiochemicals in the tomato-whitefly interaction. Among these were zingiberene and curcumene (Table I), which are apparently not only toxic (Weston et al., 1989) but also have a role as volatile cue. The major constituents of S. habrochaites f. glabratum trichomes are methylketones (Antionious et al., 2005), well known for their role in plant-insect interactions. However, with our approach, no correlation between the presence of methylketones and whitefly behavior was found.

Another important group of volatile components, the green leaf volatiles, were excluded from a role as semiochemicals in the initial whitefly-tomato interaction, as we could not detect these compounds unless tomatoes were mechanically damaged (data not shown). Terpenes are known to be constituents of essential plant oils with ecological roles in plant-insect relations, including a role as insect repellents (Bruce et al., 2005b; Johne et al., 2006; Van Tol et al., 2007). Previously, other hemiptera have been shown to be repelled by plant produced volatiles (Gibson and Pickett, 1983), and *Myzus persicae* behavioral response could be modified by altering plant terpene produc-

Specific Terpenes Can Make a Host Less Attractive

The olfactory receptor neurons in an insect’s antennae will not only detect the ratio of compounds for recognition of a host (Webster et al., 2008) but can also identify nonhost compounds acting as deterrents or alarm signals that might mask the attractiveness of the host plant (Nottingham et al., 1991). True repellence relates to a behavioral effect caused by the perception of a component at the peripheral sensory nervous system, which refrains the insect from probing and causes avoidance behavior away from the source of repellence (Pickett et al., 2008). Here, we scored repellence as a change in host choice when compounds were added to the headspace.

By correlation of headspace analyses and behavioral assays, two sesquiterpenes, zingiberene and curcumene, were identified as putatively involved in the whitefly-tomato interaction (Table I). This was corroborated in the reconstitution experiments (Fig. 3, G and H). In addition, EAG analyses confirmed both compounds to be recognized by whitefly antennae (Table III). Zingiberene readily transforms to curcumene in the presence of air (Chen and Ho, 1988). Moreover, the sensitivity of the whitefly antenna appears to be higher for curcumene (Table III), i.e. even though a blend of the two terpenes can be expected, we speculate that curcumene is detected at further distance from the odor source and therefore is most likely more responsible for the deterring effect. The toxicity of zingiberene and curcumene to insects has been shown previously in experiments with essential oils and extracts (Carter et al., 1989; Weston et al., 1989; Eigenbrode et al., 1994; Freitas et al., 2002; de Azevedo et al., 2003). Freitas et al. (2002) also showed that there is a positive and heritable relation between tomato foliar zingiberene levels and levels of *B. argentifolii* infestation. However, this correlation was scored for nymph survival in a no-choice experiment and relates to the toxic properties of zingiberene rather than to its repellent effects. Foliar application of ginger oil, containing zingiberene as the major component, appeared to be effective in protecting tomato against whitefly (Zhang et al., 2004). In their experimental setup, ginger oil appeared to repel whiteflies only at distance <1 mm from the odor source. Here, we show that treatment of a visually unaltered host with zingiberene/curcumene purified from wild tomato results in significant avoidance behavior, indicating that specific
olfactory cues are indeed an important step in host location from distance.

Of the monoterpenes associated with repellence in correlation analyses, p-cymene, α-terpinene, and α-phellandrene were positively identified as repellent compounds in bioassays (Fig. 3, A, E, and F, respectively). A mixture of p-cymene, γ-terpinene, and β-myrcene in ratios found in the most repellent S. pennellii accession LA2560 did not provide a stronger repellent effect than p-cymene alone (Fig. 3D), indicating that p-cymene is the active compound in this plant’s volatile profile. There is ample literature on the role of monoterpenes as toxins or repellents. Previously, p-cymene has been reported to be a toxic agent for the western flower thrips (Frankliniella occidentalis; Jannaert et al., 2002) and a repellent against mosquitoes (Park et al., 2003). Terpinenes and phellandrenes can be converted into p-cymene both enzymatically and through hydrogenation (LaFever and Croteau, 1993). Therefore, we hypothesize that p-cymene is the active end product in whitefly repellence. EAG analyses identified α-terpinene as the monoterpane that elicited the highest response in whitefly antennae (Table III), meaning the insect will sense this compound even when present at low concentrations. Remarkably, β-myrcene did not evoke a response in the antennae, indicating that not all volatiles in the tomato headspace are recognized by B. tabaci.

Apparantly, B. tabaci antennae are able to identify specific terpenes in their host headspace to which they zoom in. Odor cues might indicate toxic or other life-threatening environments. Whiteflies were found to be able to select their host plant based not on host quality, but possibly associated to predator related cues (Nomikou et al., 2003). So far, most research has focused on the action of terpenes as toxins or feeding deterrents. In the case of virus-transmitting insects, altering choice behavior prior to the insect’s landing and feeding is crucial to avoid the devastating effects of infection. Although new approaches with transgenic plants inhibiting viral transmission by whiteflies are also promising (Akad et al., 2007), by making use of natural plant terpenoid production, plant-insect interactions could be manipulated in such a way that it alters insect behavior and dramatically decreases the plant’s attractiveness (Degenhardt et al., 2003; Kappers et al., 2005; Schnee et al., 2006), whereas increase in other terpenes might improve resistance through the attraction of natural enemies, as described recently by Köllner et al. (2008). Breeding efforts to increase the emission of specific volatile terpenes might decrease whitefly infestation.

MATERIALS AND METHODS

Tomato and Bemisia tabaci Material and Rearing Conditions

Free-Choice Bioassays with *B. tabaci* and Tomato

Free-choice experiments with *B. tabaci* were carried out in a greenhouse compartment (28°C, relative humidity 65%). Light was supplied by high-pressure sodium lamps (Hortilux Schreder SON-T PIA G1 600W) with a photosynthetic irradiance of 250 W m⁻². The preference behavior of *B. tabaci* biotype Q (Almería population) and biotype B (Labculture Netherlands) was compared in bioassays with different wild tomatoes (LA1777, LA2560, GI1560, and *S. lycopersicum* 'Moneymaker'). Three-week-old plants were placed inside a plastic-covered wooden tray (170 × 100 × 20 cm) filled with soil, at equal distance from each other. Two or three hundred adult whiteflies were captured, placed at 4°C for 5 min, and then released in the middle of the setup. Ten and 20 min after release, settled whiteflies were recaptured, and the numbers of whiteflies on each plant were recorded. For each experiment, new, inexperienced whiteflies were used. Since no differential behavior between numbers of whiteflies on each plant were recorded. For each experiment, new, setup. Ten and 20 min after release, settled whiteflies were recaptured, and the distribution was established. Each bioassay was repeated three times in a randomized sequence.

Statistical Analyses

Absence, presence, and concentration of terpenes in different headspaces were correlated to repellence rank by multiple-linear regression analyses, and statistical significance was tested by multivariate ANOVA and nonparametric analyses. In the past few years, random forests have become a popular and widely used tool for nonparametric regression in many scientific areas. Random forest was used to validate the ranking order and to identify relevant volatiles influencing the rank variable. The random forest procedure does not require any distributional assumption because it is not model based but algorithm based (Faraway, 2006). Effect of headspace (components) to repellence was tested by one- and two-way ANOVA followed by Tukey’s test for comparison of individual means. When necessary, values were log transformed prior to analysis.

Supplemental Data

The following materials are available in the online version of this article.

Supplemental Figure S1. Dendrogram based on AFLP polymorphisms generated using the Jaccard algorithm categorizing the different *B. tabaci* populations by their genetic correlation.

Supplemental Figure S2. Mesh cover (left) placed over a tomato plant, as used in the experimental setup (see Fig. 1B), concealing its visual cues for whiteflies.

Supplemental Figure S3. Relative *B. tabaci* (biotype Q) attraction (% *n* = 200) to 72 introgression lines (S. *lycopersicum* ‘Moneyberg’ × *S. pennelli* LA716; dark bars) compared to both parents (light bars; Moneyberg [MB] and LA716).

Supplemental Table S1. List of compounds detected in wild tomato accessions (*S. pennelli*, *S. habrochaites*, and *S. peruviana*) and cultivated tomato lines (*S. lycopersicum*).

Acknowledgments

Salvador A. Gezan is kindly acknowledged for help with the statistical analyses. Ludek Tikovsky, Harold Lemeire, and Thijs Hendrix are acknowledged for taking care of the tomato collection.

Received June 9, 2009; accepted August 17, 2009; published August 19, 2009.

Literature Cited


Antonious GF, Kochhar TS, Simmons AM (2005) Natural products:...


Role of Tomato Volatiles in the Tomato-Whitefly Interaction


