

RESEARCH ARTICLE

Functional development of carbon dioxide detection in the maxillary palp of *Anopheles gambiae*

Bonaventure Aman Omondi^{1,2,*}, Shahid Majeed^{1,‡} and Rickard Ignell^{1,§}

ABSTRACT

Olfactory information drives several behaviours critical for the survival and persistence of insect pests and vectors. Insect behaviour is variable, linked to their biological needs, and regulated by physiological dynamics. For mosquitoes, CO₂ is an important cue that signifies the presence of a host, and which elicits activation and attraction. To investigate the genetic basis of olfactory modulation in mosquitoes, we assayed changes in CO₂ detection from receptor gene expression through physiological function to behaviour, associated with the onset of host seeking in the malaria vector, *Anopheles gambiae*. The gene encoding a subunit of the CO₂ receptor, *AgGr22*, was found to be significantly up-regulated in host-seeking females, consistent with a significant increase in sensitivity of CO₂-responsive neurons (cpA) housed in capitae peg sensilla of the maxillary palp. In addition, the odorant receptor *AgOr28*, which is expressed in cpC neurons, was significantly up-regulated. In contrast, *AgOr8*, which is expressed in cpB neurons, was not affected by this change in physiological state, in agreement with results for the obligate co-receptor *Orco*. Moreover, the sensitivity of the cpB neuron to (*R*)-1-octen-3-ol, a well-known mammalian kairomone, did not change in response to the onset of host seeking. The concentration of CO₂ flux influenced both the propensity of *A. gambiae* to take off into the wind and the speed with which this activation occurred. Female *A. gambiae* mosquitoes responded to CO₂ whether mature for host seeking or not, but onset of host seeking enhanced sensitivity and speed of activation at relevant doses of CO₂.

KEY WORDS: Gene expression, Modulation, Host seeking, Behaviour, Physiology, Mosquito

INTRODUCTION

Olfaction plays a vital role in the location and discrimination of resources in insects, and is a candidate target for sustainable pest control (Carey and Carlson, 2011; Pask et al., 2013; Tauxe et al., 2013). Blood-feeding insects, such as the African malaria mosquito, *Anopheles gambiae*, respond to plant volatiles and emanations from their potential blood hosts, including metabolic

by-products of animals and their cutaneous microbes (Bohbot et al., 2010; Foster and Takken, 2004; Takken and Knols, 1999; Verhulst et al., 2010). The behavioural response to these cues is not static but dependent on endogenous regulatory mechanisms related to the physiological state of the insect (Bohbot et al., 2013; Brown et al., 1994; Grant and O'Connell, 2007; Nyasembe et al., 2014). For example, upon eclosion, female *A. gambiae* do not seek blood hosts for up to 24–48 h, after which they will readily orient towards such hosts and take a blood meal (Foster and Takken, 2004). Mating is not a prerequisite for blood feeding but influences egg development in blood-fed females (Lounibos, 1994; Verhulst et al., 2010). Following a successful blood meal, these mosquitoes again ignore potential sources of a blood meal until after egg laying (Anton et al., 2007; Klowden and Briegel, 1994; Klowden and Lea, 1979a,b, 1998; Qiu et al., 2013; Takken et al., 2001). Such physiological changes provide a practical model for studying olfactory modulation in insects, especially in mosquitoes (Anton et al., 2007; Rinker et al., 2013a,b; Saveer et al., 2012). Moreover, as blood-feeding preference is a key determinant of the epidemiological role of mosquitoes as disease vectors, an understanding of its modulation has important implications for human and animal health (Carey and Carlson, 2011; Cohuet et al., 2011; Potter, 2014).

Carbon dioxide (CO₂), emitted by all potential blood hosts, is a key kairomone for mosquitoes, which signifies the presence of a blood source and sensitises them to other host sensory cues (Dekker et al., 2005; Gillies, 1980; McMeniman et al., 2014; Webster et al., 2015). Activation to CO₂ is a component of source searching, which would make the mosquito more liable to detect the source given other odours (Dekker et al., 2005; Webster et al., 2015). CO₂ is an attractant in itself, but also synergises with host odours and primes take-off, sustained flight behaviour and landing in host-seeking mosquitoes (Costantini et al., 1996; Spitzen et al., 2008; Webster et al., 2015). Flowers also emit CO₂; however, the role of this compound in floral quality evaluation in teneral stages of mosquitoes has not received particular attention, when compared with other non-blood-feeding species of insect, e.g. moths (Thom et al., 2004). Detection of CO₂ with the heteromeric gustatory receptor system is basal in several insect orders, and well conserved among insects (Robertson and Kent, 2009). In *A. gambiae*, three subunits (*AgGr22*, *AgGr23* and *AgGr24*) function together to mediate CO₂ detection (Lu et al., 2007). Functional analyses of these genes through heterologous expression (Lu et al., 2007), gene knock-out (McMeniman et al., 2014) and transient knockdown of orthologous *Grs* in the yellow fever mosquito, *Aedes aegypti* (Erdelyan et al., 2012), have suggested a conserved role of these genes as CO₂ receptors. They are expressed in one of the olfactory sensory neurons (OSNs), referred to as cpA, within the capitae peg sensilla on the maxillary palp of mosquitoes (Grant et al., 1995; Lu et al., 2007). In *A. aegypti*, these neurons exhibit an age-dependent increase in sensitivity, suggesting that changes in the sensory capability of the system are timed to occur with

¹Unit of Chemical Ecology, Department of Plant Protection Biology, Swedish University of Agricultural Sciences, Alnarp 230 53, Sweden. ²Department of Evolutionary Neuroethology, Max Planck Institute for Chemical Ecology, Hans-Knoell-Strasse 8, Jena 07745, Germany.

*Present address: Department of Entomology, University of Agriculture, PO Box 38000, Faisalabad, Punjab, Pakistan. †Present address: Bioversity International, Quartier Kabondo, Avenue du 18 Septembre 10, PO Box 1893, Bujumbura, Burundi.

§Author for correspondence (rickard.ignell@slu.se)

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution and reproduction in any medium provided that the original work is properly attributed.

the onset of host-seeking behaviour (Grant and O'Connell, 2007). Similar changes in OSN sensitivity have been observed in the cpB neuron of *A. aegypti*, which expresses the odorant receptor *Or8* along with the canonical receptor *Orco*. The latter receptor is tuned to (*R*)-1-octen-3-ol, a kairomone cue emitted by most mammals (Bohbot et al., 2013).

Transcription profiling has been used to infer the function and modulation of several insect receptors, where mRNA transcript abundance has been linked with protein (receptor) function (Abrieux et al., 2013; Bohbot et al., 2013; Iatrou and Biessmann, 2008; Poivet et al., 2013; Rinker et al., 2013a,b). Although the sensitivity of the OSNs detecting CO₂ and (*R*)-1-octen-3-ol has been shown to increase with age in *A. aegypti* (Bohbot et al., 2013; Grant and O'Connell, 2007), the relationship between transcript abundance and behaviour has yet to be investigated. We hypothesised that higher transcription would lead to increased sensitivity to a ligand, a stronger response or a wider dynamic range. This would enhance the insect's ability to detect and track fluctuations in the concentration of the ligand it perceives. In this study, we assayed gene expression and odorant detection in the maxillary palp system of *A. gambiae* to evaluate the molecular, physiological and behavioural modulation of odorant reception.

RESULTS

Gene regulation

Real-time PCR assay showed that of the three CO₂ receptor subunits, only *AgGr22* transcripts were significantly enhanced in 4 day old (4 days post-eclosion, dpe) relative to 1 dpe mosquitoes (Fig. 1; $t=5.254$, $P\leq 0.003$, d.f.=5). Similarly, odorant receptor *AgOr28* transcripts were significantly enhanced in 4 dpe compared with 1 dpe mosquitoes (Fig. 1; $t=6.746$, $P\leq 0.001$, d.f.=5); changes in the other odorant receptor transcripts were not statistically significant between age groups (Fig. 1; *AgOr8*: $t=2.304$, $P\leq 0.069$, d.f.=5; and *Orco*: $t=2.294$, $P\leq 0.070$, d.f.=5).

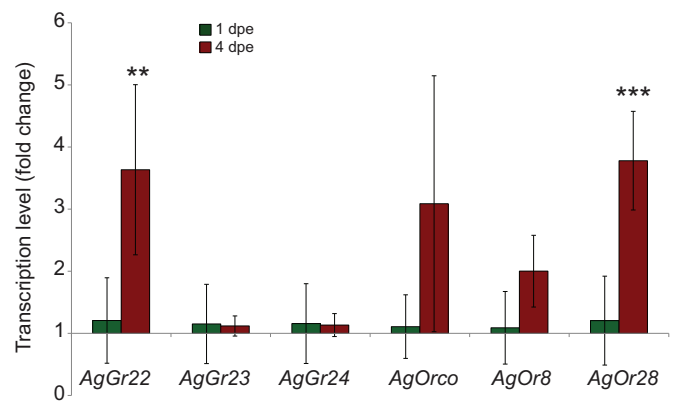


Fig. 1. Expression of the CO₂ receptor repertoire significantly increases with age. The relative transcription levels (means±s.d.) of CO₂ receptor genes (*AgGr22*, *AgGr23* and *AgGr24*) and odorant receptor genes (*AgOrco*, *AgOr8* and *AgOr28*) in 1 and 4 day old (1 and 4 days post-eclosion, dpe) *Anopheles gambiae*. Relative transcription level increases significantly (** $P<0.01$) for *AgGr22* but not for the other two subunits, and for *AgOr28* but not for the other *AgOr* transcripts over the same period.

Neural activity

Single sensillum recordings (Fig. 2A) showed a significantly enhanced response to CO₂ in 4 dpe relative to 1 dpe mosquitoes at all concentrations above 600 ppm, with a significant interaction between age and treatment ($F_{5,108}=4.83$, $P\leq 0.0005$; Fig. 2B). Moreover, 4 dpe mosquitoes had a lower CO₂ detection threshold than 1 dpe mosquitoes (Fig. 2B). Detection threshold and strength of response to (*R*)-1-octen-3-ol were not significantly different between 1 and 4 dpe mosquitoes (Fig. 2C).

Activation by CO₂

In the bioassay, optimum CO₂ activation occurred between 600 and 1200 ppm for both age classes, but 4 dpe mosquitoes were

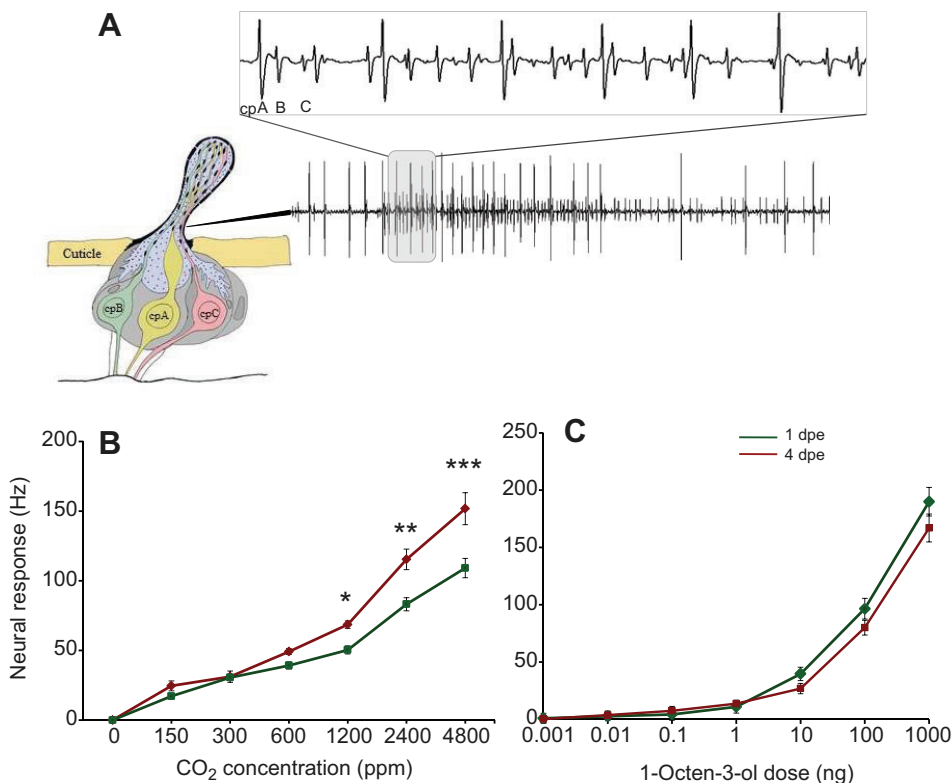


Fig. 2. The sensitivity of the CO₂ olfactory sensory neurons (OSNs) is correlated with receptor transcription. (A) The capitulate peg sensillum houses three neurons, classified according to spike amplitude: cpA expresses the three subunits, *Gr22–24*, that mediate CO₂ detection, cpB expresses *Or8* and *Orco*, which respond to (*R*)-1-octen-3-ol, while cpC expresses *Or28* and *Orco*. (B) The sensitivity of cpA to CO₂ is increased in 4 dpe relative to 1 dpe mosquitoes. (C) cpB does not change its sensitivity to (*R*)-1-octen-3-ol over the same time period. * $P<0.05$, ** $P<0.01$, *** $P<0.001$.

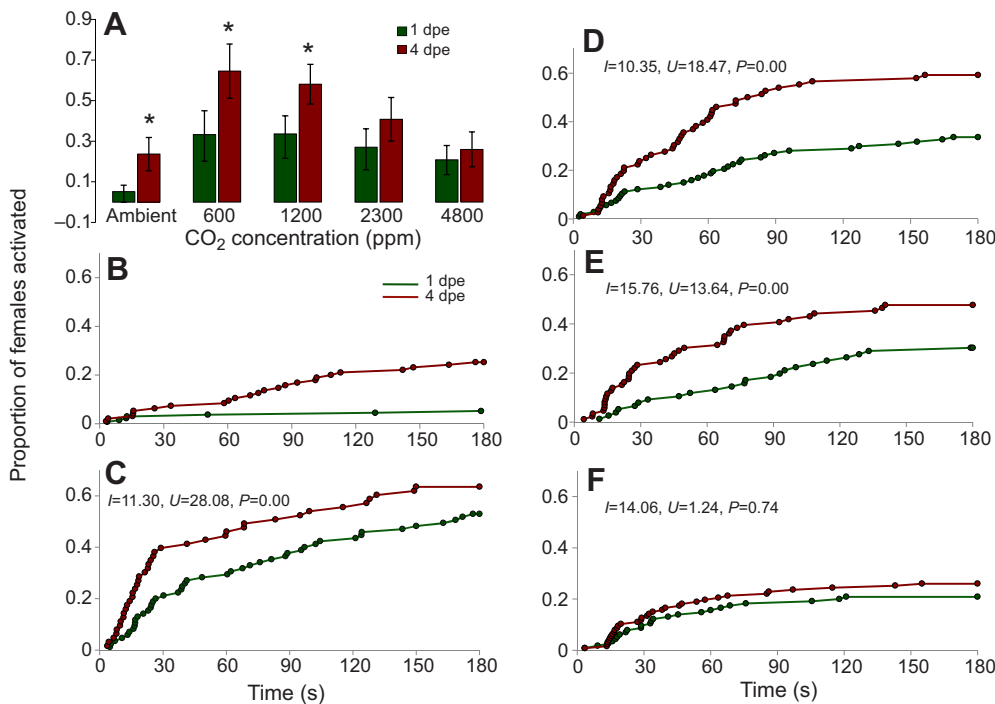


Fig. 3. Activation profiles of 1 and 4 dpe *A. gambiae* females by CO₂ flux is dependent on the concentration of CO₂. (A) Both 1 and 4 dpe mosquitoes are activated by CO₂ but at different rates, both with an optimum range of 600–1200 ppm. Error bars represent the 95% confidence interval for binomial probability for each result (see also Table 2). * $P < 0.05$. (B–F) Stimulation by CO₂ above ambient levels increased the propensity and speed of activation [B, 380 ppm (ambient); C, 600 ppm; D, 1200 ppm; E, 2400 ppm; F, 4800 ppm]. Most mosquitoes take off as soon as CO₂ is detected, giving a positive skew to the response–time function relative to the diagonal line (describing uniform interval activation).

more responsive to CO₂ stimulation at these concentrations (Fig. 3A). At ambient CO₂ stimulation, the activation pattern was similar to random uniform flight with only <5% of mosquitoes activated (Cox–Mantel test, $I = 5.55$, $U = 0.71$, $P \leq 0.76$; and $I = 3.21$, $U = -0.70$, $P \leq 0.69$ for 1 and 4 dpe mosquitoes, respectively; Fig. 3B). Enhanced levels of CO₂ above ambient concentration, however, resulted in both a greater proportion of mosquitoes activated and faster instantaneous activation of both age classes compared with random uniform activation, resulting in activation functions described by a convex-shaped line compared with the hypothetical diagonal line between the origin and maximum activation (Fig. 3C,D, Table 1). A significantly higher proportion of 4 dpe mosquitoes were activated by all CO₂ treatment levels, but at 4800 ppm CO₂ a lower activation rate occurred, resulting in a diminished difference between the two age classes (Fig. 3).

Table 1. Median instantaneous activation time varies significantly between 1 and 4 dpe *Anopheles gambiae* according to CO₂ concentration

CO ₂ concentration ppm	Median activation time (s)		Sample size (n/N)	
	1 dpe	4 dpe	1 dpe	4 dpe
380	12.64 ^{a,A}	75.72 ^{a,A}	8/135	24/95
600	41.31 ^{a,A}	23.27 ^{a,B}	45/85	41/63
1200	56.81 ^{a,A,B}	44.84 ^{a,B}	36/107	45/76
2400	76.94 ^{a,C}	38.77 ^{b,B}	23/85	41/86
4800	33.15 ^{a,B}	31.47 ^{a,B}	24/114	33/128

Comparisons are based on survival functions across groups defined by CO₂ dose and mosquito age (dpe, days post-eclosion). Medians with the same letters denote activation functions that are not significantly different between CO₂ concentrations within an age class (uppercase) and between age classes within a CO₂ dose level (lowercase) (Cox–Mantel test, $P \leq 0.05$). For each treatment the sample sizes (N , number of mosquitoes tested; n , number of respondents) are given.

DISCUSSION

The olfactory receptors expressed in the maxillary palps of *A. gambiae* are active within 24 h of emergence, but undergo transcriptional changes as the mosquito matures for blood-host seeking. Increased transcription of a subunit of the CO₂ receptor (AgGR22) is mirrored in increased neural and behavioural sensitivity to CO₂. Behavioural activation by CO₂ was greatest at low concentrations (600–1200 ppm). Higher concentrations in fact reduced activation of both 1 and 4 dpe female *A. gambiae*, even though the highest concentration tested was just 10% of that in human breath. The cpC-expressed receptor (AgOR28) was also significantly up-regulated. This receptor is less specific than other maxillary palp receptors, with several potential ligands identified, and their behavioural function has not yet been ascribed (Lu et al., 2007; Smallegange et al., 2012). The transcript levels of the rest of the receptor genes, *AgOrco*, *AgOr8*, *AgGr23* and *AgGr24*, were not significantly changed between 1 and 4 dpe, consistent with the functional stability of AgOR8-expressing OSNs. Although we did not test the receptor protein abundance in the neurons directly, these results show a correlation between transcript abundance and physiological activity in two different receptors, suggesting a direct relationship between transcription and the role of the ligand, decoded in behaviour under specific physiological conditions.

Activation of functionally required receptor proteins enables an efficient use of energy while amplifying a signal whose importance is relevant to a specific physiological state (Rinker et al., 2013a; Webster et al., 2015). The ORs and GRs are heteromers (Larsson et al., 2004; Sato et al., 2008), so one would expect that an equimolar presence of the receptor subunits would be necessary for optimal function (Bohbot et al., 2013). The regulation of a single subunit of the heteromeric receptors in both the OR and GR systems suggests a very simplified modulation mechanism, which changes a necessary and sufficient component to achieve down- or up-regulation of function. Lu et al. (2007) showed that *Gr22* is necessary for CO₂ detection in *A. gambiae*, while Sengul and Tu (2008) and McMeniman et al. (2014) demonstrated that the knockdown of the

Table 2. Details of the gene and primer sequences used for qPCR assay

Gene name	Primer	Sequence 5' to 3'	Product (bp)		Citation
			cDNA	gDNA	
Ribosomal protein S7	AgRpS7F AgRpS7R	CACCGCCGTGTACGATGCCA ATGGTGGTCTGCTGGTTCTT	132	132	Pelletier and Leal, 2011
α -Tubulin elongation factor	EF1 α -F EF1 α -R AgDLAPF AgDLAPR	TGGAAAGCGTCCCTTGTCAG GCCATGCTCCAGACAGTACA TTCTGGGATATGCCGATTTC TGGGGCTCCATACTTCAGAC	186	752+186	Ponton et al., 2011
TATAA box binding protein	AgTBPF AgTBPR	CTGTCCGAGATCAGAAAGCAC ATCCACCCATCCAGGTAGAGT	151	–	This study
Ubiquitin	UBQ-F UBQ-R	GCAAGCTAGTAGTGCCGTCTG TCGCGTGTGTGATTATTTCAG	190	–	Robertson and Kent, 2009
Ribosomal protein L13	RpL13F RpL13R	ATCCTGTCTGGTAACTCGGTG CCTTCCACAACATACGGCTC	169	83+169	Robertson and Kent, 2009
Ribosomal protein S4	RpS4F RpS4R	CGAGGTGACGAAGATTGTGA AAGTATTCCGCCGTCTTGTG	124	124	This study
CO ₂ co-receptor	GR22F GR22R GR23F GR23R AgGR24F AgGR24R	TTTGCAACGAAGCTCATCAC GCGTACCCGTCAAGATTCAT ATGAATCCGGCAATCGTAAG ACTGCAGCAAAACGATCAGA TGAAAGCTCCAAACCGATCT ATGTACACGGTGAGCAGCAG	166	419+166	This study
OR co-receptor	AgOrcoF AgOrcoR	GACTATTTCCGGAGCCAAGTTT CAGCACCATGAAGTAGGTGACA	88	122+88	This study
Odorant receptor	AgOr8-F AgOr8-R AgOr28F AgOr28R	TGCAGGTCTTTCTGCTGTGTTAC TGGAGAATTTACGGCAGTC CCATCCTGCAGCTCTTTCTG GGTTTGCAGCGTAACCATGT	177	199+92	latrou and Biessmann, 2008
			200	–	latrou and Biessmann, 2008

–, intron straddling.

orthologous gene (*Gr2*) in *A. aegypti* was sufficient to abolish CO₂ detection. These observations are consistent with our finding. Contrary to our results, Bohbot et al. (2013) reported up-regulation of all olfactory receptors expressed in the maxillary palps of *A. aegypti* throughout maturation (1, 6 and 10 dpe) and linked this to cellular and behavioural responses. Although we used two different quantification and expression normalisation protocols, this difference would nevertheless point to an interesting biological difference between Culicine and Anopheline mosquitoes. In *Anopheles*, changes associated with host seeking appear to involve regulation of only a subset of receptors, implying that a small subset of the odour space may drive host seeking. It would be interesting to compare this among closely related species with divergent host-seeking strategies (specialists and opportunists).

Modulatory mechanisms may shape the contextual meaning of a single olfactory signal. CO₂ has previously been reported to be associated with the host-seeking behaviour of mosquitoes (Bohbot et al., 2013; Grant and O'Connell, 2007), consistent with our observations. CO₂ is a ubiquitous compound whose fluctuation in regular pulses above ambient is a reliable indicator of vertebrate blood hosts for mosquitoes. However, inconsistencies in the effectiveness of CO₂-based traps to catch mosquitoes suggest that anthropophilic vectors do not depend solely on this chemical cue to locate humans (Costantini et al., 1996; Takken and Knols, 1999). Thus, an understanding of the stability of the CO₂ plume structure and the functional role of CO₂ will be important issues to resolve in the future. The observation that 4 day old mosquitoes were more easily stimulated to fly with ambient CO₂ levels supports the earlier observation that host-seeking input has a non-neuronal maturation component other than the receptor function (McMeniman et al., 2014). *Aedes aegypti*, however, do not get activated by CO₂ unless mature enough to blood feed at 6 and 10 dpe, respectively (Bohbot et al., 2013; Grant et al., 1995). Interestingly, we also observed

dose-dependent behavioural response to CO₂ in 1 dpe mosquitoes, suggesting that this compound is not restricted to blood host location. The functional and behavioural dynamic range of CO₂ observed is consistent with concentrations that would be expected in the medium to long range following dilution of the 40,000 ppm CO₂ exhaled by humans, for example.

The observed functional changes in receptor transcripts and neurons suggest an association of sensory signals with physiological needs. The cpB neuron expresses *AgOr8/AgOrco*, which showed stable transcription and unchanged sensitivity to its key ligand (*R*)-1-octen-3-ol between 1 and 4 dpe, unlike in *A. aegypti*, where it is up-regulated and the receptor sensitivity increased (Bohbot et al., 2013). As *AgOr8* is exclusively expressed in adults, this implies that transcriptional changes during pupation deliver a fully functional receptor at eclosion, and that (*R*)-1-octen-3-ol may be used at both nectar-feeding and host-seeking stages, or that its importance at host seeking is dependent on co-detection with another compound. (*R*)-1-Octen-3-ol is also a common compound emitted by fungi (Inamdar et al., 2013). Therefore, its role in the context of sugar source seeking would be interesting to investigate.

The significant up-regulation of *AgOr28* transcripts suggests that the key ligand(s) of this receptor is important in the host-seeking behaviour of *A. gambiae*. Heterologously expressed *AgOr28* is more broadly tuned compared with *AgOr8*, responding to 2,4,5-trimethylthiazole, acetophenone, 2-acetylthiophene and fenchone, all of which are associated with mammalian odour (Carey et al., 2010; Lu et al., 2007; Xia et al., 2008). Addition of either acetophenone or 2-acetylthiophene to a basic human odour blend decreased landing of *A. gambiae* (Smallegange et al., 2012), suggesting that this receptor may be involved in mosquito host selection or discrimination.

We show that peripheral modulation may explain behavioural changes towards host seeking and demonstrate a correlation

between receptor gene expression, neuronal sensitivity and behaviour. Receptor sensitivity reliably modulates the olfactory signal and contextual relevance of components of an odour plume, and might also sharpen host selection. As the maxillary palp system is a secondary olfactory organ, an investigation of the functional structure of an odour plume, involving antenna-expressed receptors, would be interesting. Such studies would also reveal suitable candidates for molecular manipulation of mosquito behaviour towards sustainable control of the diseases they transmit.

MATERIALS AND METHODS

Mosquitoes

Anopheles gambiae sensu stricto (Suakoko strain, now renamed *Anopheles colluzzi*; Coatzee et al., 2015), were reared according to standard protocols (<http://www.mr4.org>). Larvae were reared in plastic trays (30×15×5 cm), half-filled with distilled water, and fed every other day on Tetramin Baby fish food (Tetra GmbH, Germany). Rearing medium was refreshed with distilled water every other day. Pupae were collected into adult rearing cages (30×30×30 cm; Bugdorm, MegaView Science, Taiwan) and allowed 24 h to eclose. Adult mosquitoes were fed on 10% sucrose solution *ad libitum*. When needed for colony maintenance, adults were fed on human blood by offering a human arm for 30 min. Non-blood-fed female mosquitoes, either 1 dpe (12–24 h) or 4 dpe, were used for experiments.

RNA extraction and qPCR

The transcript abundance of receptor genes was compared between paired 1 and 4 dpe female *A. gambiae* in six biological replicates. For each replicate, a single cohort of mosquito pupae was divided into two cages (ca. 60 pupae each) and allowed to eclose: the mosquitoes in one cage were killed the day after emergence, and those in the other cage at 4 days post-emergence to constitute a single replicate of paired treatments. Maxillary palps and proboscis of female mosquitoes from each treatment group were dissected into 300 µl Trizol (Invitrogen Corporation, Life Technologies, Carlsbad, CA, USA) and stored at –80°C until RNA extraction. All dissections occurred between 14:00 h and 16:00 h to limit potential circadian changes in gene expression. The olfactory tissues of the two treatment groups were processed side by side until the reverse transcription (RT) step to minimise variation arising from day-to-day differences, as the biological replicates and the RT step had been shown in a nested pilot study to be the greatest sources of variation. Total RNA was extracted in 500 µl Trizol reagent according to the manufacturer's protocol. The RNA pellet was washed in 70% ethanol and then in 90% ethanol, dried briefly and re-suspended in 30 µl RNase-free water (Bio-Rad Laboratories, Inc., Hercules, CA, USA) on ice. RNA was quantified using absorbance measure (Nanodrop 2000c, Thermo Scientific, Wilmington, DE, USA) prior to DNase treatment. Treatment with TURBO DNase (Ambion, Life Technologies) was immediately carried out according to the manufacturer's protocol and the reaction stopped using TURBO DNase inactivator (Ambion, Life Technologies). The supernatant was immediately used for the RT step using the iSCRIPT reaction mix (Bio-Rad Laboratories, Inc.) in three technical replicates. A 1:1 mix of oligo-dT and random hexamer primers was used, in final volumes of 20 µl each, containing 8 µl of the RNA sample. The cDNA sample was diluted three times with PCR grade water to obtain the template for qPCR assays.

Primer design

All primers were designed using Primer 3 software (www.justbio.com) from available *A. gambiae* genome sequence information (www.vectorbase.org). All primers were designed to have a melting temperature (T_m) of 60°C and a product size of 120–180 bp. Primer pairs were generally designed in adjacent exons or were intron straddling so as to exclude genomic DNA from the qPCR. Three sets of primers were designed for each target, usually in the first two exons to maximise product independent of RT efficiency. The best primer combinations were selected by analysing the specificity and compatibility of each primer set *in silico* using BLASTn and Oligoanalyzer (Integrated DNA Technologies; <http://eu.idtdna.com/analyzer/Applications/OligoAnalyzer>). The best two combinations were tested by qPCR and a

selection made by comparing the consistency of amplification in three technical replicates.

Reference genes

RpS7 and *RpL18* genes are the most commonly used reference genes for the quantification of transcripts in mosquito olfactory tissue (Iatrou and Biessmann, 2008; Pelletier and Leal, 2011; Sengul and Tu, 2008; Lavazec et al., 2007). However, as we found no report of the systematic testing of these genes in treatments and tissues similar to those used in this study, six other genes, commonly used in insect qPCR studies, were obtained and tested to produce the most stable combinations for this study (Bustin et al., 2009; Omondi et al., 2015) (Table 2). The expression was normalised to a reference factor comprising the geometric means of the best combination reference genes in Genex version 5 (MultiD Systems, Göteborg, Sweden).

Quantitative real-time PCR

Quantitative PCR was done using the SYBR Green fluorescent dye for product detection. The reaction was carried out in a 20 µl reaction mix containing 10 µl iQ Supermix (Bio-Rad Laboratories, Inc.), 200 µmol l⁻¹ of each primer mix, 1.5 µl cDNA sample and PCR grade water. Amplification was done on a BIORAD CFX 96 (Bio-Rad Laboratories, Inc.), using the following programme: a single 10 min cycle at 94°C, followed by 40 cycles of 12 s each at 95, 59 and 72°C. Data acquisition was done for each cycle just following each elongation step. A high resolution melting analysis (65 to 94°C in 0.5°C steps) was done to test the fidelity of the PCR. For each plate and primer set, a no-template and no-RT control was included. The transcript levels of each of the chemoreceptor genes previously shown to be expressed in the maxillary palp of *A. gambiae* (*AgGr22*, *AgGr23*, *AgGr24*, *AgOrco*, *AgOr8* and *AgOr28*; Lu et al., 2007) and of potential reference genes were assayed for each treatment.

Single sensillum recordings

Single unit electrophysiology was performed with sharpened tungsten electrodes from the capitata peg sensilla of the maxillary palps of female *A. gambiae*, as previously described (Bohbot et al., 2010). A single set of recordings from the cpA and cpB neurons across a dose spectrum of CO₂ and (*R*)-1-octen-3-ol, respectively, was taken from each preparation, with 10 replicates. A mounted 1 or 4 dpe female mosquito was placed in front of a continuous humidified stream of synthetic air (80% nitrogen, 20% oxygen; Strandmöllen AB, Ljungby, Sweden), which passed over the maxillary palp via a glass tube (7 mm i.d.) at 1.5 l min⁻¹. Delivery of CO₂ was regulated by two-way Teflon solenoid valves (Teddington, Skogås, Sweden) controlled via the digital output of an IDAC-4 (Syntech, Germany). The valves were connected to gas cylinders containing metered amounts of CO₂ (150, 300, 600, 1200, 2400, 4800 ppm) and oxygen (20%), balanced by nitrogen (Strandmöllen AB). (*R*)-1-Octen-3-ol (a gift from James Logan, Rothamsted Research, UK; CAS: 3391-86-4), dissolved in GC-grade hexane (99.9% purity, Sigma-Aldrich), was used to describe the dose–response relationship of cpB. Pasteur pipettes (VWR International) containing a piece of filter paper (5×10 mm) (Whatman, GE Healthcare, UK) were loaded with 10 µl each of a (*R*)-1-octen-3-ol solution in a series of increasing concentrations (0.001–1000 ng µl⁻¹). All pipettes were prepared in a fume hood and left for 30 min for the solvent to evaporate prior to use. In all experiments, insects were presented with a stimulus for 0.5 s, and pipettes were replaced between replicates.

Behavioural assay

A glass non-choice bioassay tube, 80×9.5 cm i.d. (Majeed et al., 2014), with a laminar flow (20 cm s⁻¹ wind speed) was used to assay the response of mosquitoes at each age to 380 (ambient), 600, 1200, 2400 and 4800 ppm CO₂. CO₂ stimulation was turned on or off manually by directing the inlet from the controller either into the bioassay tube or into the exhaust tube, to avoid pre-exposure of test animals to unintended doses of CO₂. The CO₂ pulses of 0.5 s on/2 s off, embedded within the background of ambient CO₂, were generated by the stimulus controller (IDAC-4, Syntech, Kirchzarten, Germany) through two-way Teflon solenoid valves (Teddington, Lanna, Sweden) to simulate human host breath (Dekker et al., 2005). Air intake into

the tube was charcoal filtered, and humidified (69–85% RH), with a pulse originating from pure CO₂ (Strandmöllen AB) to produce the desired mix. Between each test, CO₂ levels were monitored at the downwind end of the bioassay using a CO₂ analyser (LI-820, LI-COR Biosciences, Lincoln, NE, USA). Wind speed and stability of flow were tested using an anemometer (ThermoAir3, Schiltknecht Messtechnik AG, Switzerland). Mosquitoes to be tested were starved (*ad libitum* access to water only) for 12 h prior the test. Females were then transferred into release cages and kept in the bioassay room for 6 h prior to use, under the same conditions as during rearing and with *ad libitum* access to water through a moist cotton ball. Release cages consisted of a Perspex tube of the same diameter as the bioassay tube, sealed at one end with 1.0 mm gauge netting and with a rotating mesh covering the door at the other end. The release cages with test insects were set into the bioassay under red light (~280 lx) and left for ca. 10 min to allow the mosquitoes to acclimatise, after which the butterfly door of the release cage was carefully opened. Testing was done between 20:00 h and 22:00 h, representing the first quarter of the scotophase. For each insect, the time taken to activation was recorded. Non-responders by 3 min were included in the analysis as censored individuals and contributed to the determination of activation levels per group. In total, 63–135 insects were tested per treatment (Table 1).

Data analysis

Gene expression levels were determined using the $\Delta\Delta C_q$ method (Livak and Schmittgen, 2001) on Genex Version 5 (Multi D Systems, Sweden). Gene expression levels per sample were normalised to a reference factor comprising the geometric means of the three most stable reference genes, and expressed relative to the mean of the control group (1 dpe) females. Transcription levels were compared between genes per group (1 and 4 dpe) using a two-tailed paired Student's *t*-test implemented in Genex v5 after checking data for normality and homogeneity of residuals using Kolmogorov's test. Statistical significance values were adjusted for multiple comparisons.

Repeated measures 2-way ANOVA, followed by a Bonferroni *post hoc* test, was performed to compare the physiological activity between 1 and 4 dpe female mosquitoes with each ligand dosage using Statistica Version 8 (Statsoft, 2007). The interaction between independent variables (age and concentration) was assessed. A binomial function was used to test the proportion of mosquitoes taking flight and to calculate the confidence interval of the result for each treatment at $P \leq 0.05$ in R (R Development Core Team, 2011). The probability of activation function (Kaplan–Meier survivorship function) was compared among respondents using the Cox–Mantel test to test the null hypothesis that activation probability functions do not differ between pairs of age and CO₂ activation regimes using Statistica. A censure variable was used, enabling the non-responders to contribute to the observation.

Acknowledgements

We thank Dr James Logan (Rothamsted Research) for kindly providing (R)-1-octen-3-ol used in the study, and Dr Teun Dekker [Swedish University of Agricultural Sciences (SLU)] for help with the setup of the CO₂ stimulation system. We are grateful to Dr David Carrasco (SLU), for advice on statistical analysis, Dr Julien Pelletier, Keele University (UK) for support with the qPCR assay and for comments on earlier versions of the manuscript. We also thank Dr Jose-Manuel Estivalis (FIOCRUZ, Brazil), and members of the disease vector group at the Chemical Ecology Unit (SLU Alnarp) for valuable feedback on the manuscript.

Competing interests

The authors declare no competing or financial interests.

Author contributions

B.A.O. and R.I. designed the study, S.M. carried out SSR for the experiment resulting in Fig. 2. B.A.O. carried out the rest of the experiments, analysed the data and wrote the manuscript. R.I. edited the manuscript, supervised the study and sourced funding.

Funding

This study was supported by the Linnaeus initiative 'Insect Chemical Ecology, Ethology and Evolution' IC-E3 (Formas, SLU). B.A.O. was supported by a Max

Planck Grant for Foreign Cooperation in SLU, Alnarp. Deposited in PMC for immediate release.

References

- Abrieux, A., Debernard, S., Maria, A., Gaertner, C., Anton, S., Gadenne, C. and Duportets, L. (2013). Involvement of the G-protein-coupled dopamine/ecdysteroid receptor DopEcR in the behavioral response to sex pheromone in an insect. *PLoS ONE* **8**, e72785.
- Anton, S., Dufour, M.-C. and Gadenne, C. (2007). Plasticity of olfactory-guided behaviour and its neurobiological basis: lessons from moths and locusts. *Entomol. Exp. Appl.* **123**, 1–11.
- Bohbot, J. D., Lu, T. and Zwiebel, L. J. (2010). Molecular regulation of olfaction in mosquitoes. In *Ecology and Control of Vector-Borne Diseases*, Vol. 2, *Olfaction in Vector-Host Interactions* (ed. W. Takken and B. G. J. Knols), pp. 17–38. Wageningen: Academic Publishers.
- Bohbot, J. D., Durand, N. F., Vinyard, B. T. and Dickens, J. C. (2013). Functional development of the octenol response in *Aedes aegypti*. *Front. Physiol.* **4**, e39.
- Brown, M. R., Klowden, M. J., Crim, J. W., Young, L., Shrouder, L. A. and Lea, A. O. (1994). Endogenous regulation of mosquito host-seeking behavior by a neuropeptide. *J. Insect Physiol.* **40**, 399–406.
- Bustin, S. A., Benes, V., Garson, J. A., Hellems, J., Huggett, J., Kubista, M., Mueller, R., Nolan, T., Pfaffl, M. W., Shipley, G. L. et al. (2009). The MIQE guidelines: minimum information for publication of quantitative real-time PCR experiments. *Clin. Chem.* **55**, 611–622.
- Carey, A. F. and Carlson, J. R. (2011). Insect olfaction from model systems to disease control. *Proc. Natl. Acad. Sci. USA* **108**, 12987–12995.
- Carey, A., Wang, G., Su, C.-Y., Zwiebel, L. J. and Carlson, J. R. (2010). Odorant reception in the malaria mosquito *Anopheles gambiae*. *Nature* **464**, 66–71.
- Coatzee, M., Hunt, H. R., Wilkerson, R., Della-Torre, A., Coulibaly, M. B. and Besansky, N. J. (2015). *Anopheles coluzzii* and *Anopheles amharicus*, new members of the *Anopheles gambiae* complex. *Zootaxa* **3619**, 246–274.
- Cohuet, A., Harris, C., Robert, V. and Fontenille, D. (2011). Evolutionary forces on *Anopheles*: what makes a malaria vector? *Trends Parasitol.* **26**, 130–136.
- Costantini, C., Gibson, G., Sagnon, N., Della Torre, A., Brady, J. and Coluzzi, M. (1996). Mosquito responses to carbon dioxide in B West African Sudan savanna village. *Med. Vet. Entomol.* **10**, 220–227.
- Dekker, T., Geier, M. and Cardé, R. T. (2005). Carbon dioxide instantly sensitizes female yellow fever mosquitoes to human skin odours. *J. Exp. Biol.* **208**, 2963–2972.
- Erdelyan, C. N. G., Mahood, T. H., Bader, T. S. Y. and Whyard, S. (2012). Functional validation of the carbon dioxide receptor genes in *Aedes aegypti* mosquitoes using RNA interference. *Insect Mol. Biol.* **21**, 119–127.
- Foster, W. A. and Takken, W. (2004). Nectar-related vs. human-related volatiles: behavioural response and choice by female and male *Anopheles gambiae* (Diptera: Culicidae) between emergence and first feeding. *Bull. Entomol. Res.* **94**, 145–157.
- Gillies, M. T. (1980). The role of carbon dioxide in host-finding by mosquitoes (Diptera: Culicidae): a review. *Bull. Entomol. Res.* **70**, 525–532.
- Grant, A. J. and O'Connell, R. J. (2007). Age-related changes in female mosquito carbon dioxide detection. *J. Med. Entomol.* **44**, 617–623.
- Grant, A. J., Aghajanian, J. G., O'Connell, R. J. and Wigton, B. E. (1995). Electrophysiological responses of receptor neurons in mosquito maxillary palp sensilla to carbon dioxide. *J. Comp. Physiol. A* **177**, 389–396.
- Iatrou, K. and Biessmann, H. (2008). Sex-biased expression of odorant receptors in antennae and palps of the African malaria vector *Anopheles gambiae*. *Insect Biochem. Mol. Biol.* **38**, 268–274.
- Inamdar, A. A., Hossain, M. M., Bernstein, A. I., Miller, G. W., Richardson, J. R. and Bennett, J. W. (2013). Fungal-derived semiochemical 1-octen-3-ol disrupts dopamine packaging and causes neurodegeneration. *Proc. Natl. Acad. Sci. USA* **110**, 19561–19566.
- Klowden, M. J. and Briegel, H. (1994). Mosquito gonotrophic cycle and multiple feeding potential: contrasts between *Anopheles* and *Aedes* (Diptera: Culicidae). *J. Med. Entomol.* **31**, 618–622.
- Klowden, M. J. and Lea, A. O. (1979a). Abdominal distention terminates subsequent host-seeking behaviour of *Aedes aegypti* following a blood meal. *J. Insect Physiol.* **25**, 583–585.
- Klowden, M. J. and Lea, A. O. (1979b). Humoral inhibition of host-seeking in *Aedes aegypti* during oöcyte maturation. *J. Insect Physiol.* **25**, 231–235.
- Klowden, M. J. and Lea, A. O. (1998). Blood meal size as a factor affecting continued host-seeking by *Aedes aegypti* (L.). *Am. J. Trop. Med. Hyg.* **27**, 827–831.
- Larsson, M. C., Domingos, A. I., Jones, W. D., Chiappe, M. E., Amrein, H. and Vosshall, L. B. (2004). Or83b encodes a broadly expressed odorant receptor essential for *Drosophila* olfaction. *Neuron* **43**, 703–714.
- Lavazec, C., Boudin, C., Lacroix, R., Bonnet, S., Diop, A., Thiberge, S., Boisson, B., Tahar, R. and Bourgoin, C. (2007). Carboxypeptidases B of *Anopheles gambiae* as targets for a *Plasmodium falciparum* transmission-blocking vaccine. *Infect. Immun.* **75**, 1635–1642.

- Livak, K. J. and Schmittgen, T. D.** (2001). Analysis of relative gene expression data using real-time quantitative PCR and the 2(-delta delta C(T)) method. *Methods* **25**, 402-408.
- Lounibos, L. P.** (1994). Variable egg development among *Anopheles (Nyssorhynchus)*: control by mating? *Phys. Entomol.* **19**, 51-57.
- Lu, T., Qiu, Y. T., Wang, G., Kwon, J. Y., Rutzler, M., Kwon, H.-W., Pitts, R. J., van Loon, J. J. A., Takken, W., Carlson, J. R. et al.** (2007). Odor coding in the maxillary palp of the malaria vector mosquito *Anopheles gambiae*. *Curr. Biol.* **17**, 1533-1544.
- Majeed, S., Hill, S. R. and Ignell, R.** (2014). Impact of elevated CO₂ background levels on the host-seeking behaviour of *Aedes aegypti*. *J. Exp. Biol.* **217**, 598-604.
- McMeniman, C. J., Corfas, R. A., Matthews, B. J., Ritchie, S. A. and Vosshall, L. B.** (2014). Multimodal integration of carbon dioxide and other sensory cues drives mosquito attraction to humans. *Cell* **156**, 1060-1071.
- Nyaseembe, V. O., Teal, P. E. A., Sawa, P., Tumlinson, J. H., Borgemeister, C. and Torto, B.** (2014). *Plasmodium falciparum* infection increases *Anopheles gambiae* attraction to nectar sources and sugar uptake. *Curr. Biol.* **24**, 217-221.
- Omondi, B. A., Latorre-Estivalis, J. M., Oliveira, I. H. R., Ignell, R. and Lorenzo, M. G.** (2015). Evaluation of reference genes for insect olfaction studies. *Parasite Vector* **8**, 243.
- Pask, G. M., Bobkov, Y. V., Corey, E. A., Ache, B. W. and Zwiebel, L. J.** (2013). Blockade of insect odorant receptor currents by amiloride derivatives. *Chem. Senses* **38**, 221-229.
- Pelletier, J. and Leal, W. S.** (2011). Characterization of olfactory genes in the antennae of the Southern house mosquito, *Culex quinquefasciatus*. *J. Insect Physiol.* **57**, 915-929.
- Poivet, E., Gallot, A., Montagné, N., Glaser, N., Legeai, F. and Jacquin-Joly, E.** (2013). A comparison of the olfactory gene repertoires of adults and larvae in the noctuid moth *Spodoptera littoralis*. *PLoS ONE* **8**, e60263.
- Ponton, F., Chapuis, M.-P., Pernice, M., Sword, G. A. and Simpson, S. J.** (2011). Evaluation of potential reference genes for reverse transcription-qPCR studies of physiological responses in *Drosophila melanogaster*. *J. Insect Physiol.* **57**, 840-850.
- Potter, C. J.** (2014). Stop the biting: targeting a mosquito's sense of smell. *Cell* **156**, 878-881.
- Qiu, Y.-T., Gort, G., Torricelli, R., Takken, W. and van Loon, J. J. A.** (2013). Effects of blood-feeding on olfactory sensitivity of the malaria mosquito *Anopheles gambiae*: application of mixed linear models to account for repeated measurements. *J. Insect Physiol.* **59**, 1111-1118.
- R Development Core Team** (2011). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. <http://www.R-project.org/>.
- Rinker, D. C., Pitts, R. J., Zhou, X., Suh, E., Rokas, A. and Zwiebel, L. J.** (2013a). Blood meal-induced changes to antennal transcriptome profiles reveal shifts in odor sensitivities in *Anopheles gambiae*. *Proc. Natl. Acad. Sci. USA* **110**, 8260-8265.
- Rinker, D. C., Zhou, X., Pitts, R. J., The AGC Consortium, Rokas, A. and Zwiebel, L. J.** (2013b). Antennal transcriptome profiles of anopheline mosquitoes reveal human host olfactory specialization in *Anopheles gambiae*. *BMC Genomics* **14**, 749.
- Robertson, H. M. and Kent, L.** (2009). Evolution of the gene lineage encoding the carbon dioxide receptor in insects. *J. Insect Sci.* **9**, 19.
- Sato, K., Pellegrino, M., Nakagawa, T., Nakagawa, T., Vosshall, L. B. and Touhara, K.** (2008). Insect olfactory receptors are heteromeric ligand-gated ion channels. *Nature* **452**, 1002-1006.
- Saveer, A. M., Kromann, S. H., Birgersson, G., Bengtsson, M., Lindblom, T., Balkenius, A., Hansson, B. S., Witzgall, P., Becher, P. G. and Ignell, R.** (2012). Floral to green: mating switches moth olfactory coding and preference. *Proc. R. Biol. Soc. B Biol. Sci.* **279**, 2314-2322.
- Sengul, M. S. and Tu, Z.** (2008). Characterization and expression of the odorant-binding protein 7 gene in *Anopheles stephensi* and comparative analysis among five mosquito species. *Insect Mol. Biol.* **17**, 631-645.
- Smallegange, R. C., Bukovinszkiné-Kiss, G., Otieno, B., Mbadi, P. A., Takken, W., Mukabana, W. R. and van Loon, J. J. A.** (2012). Identification of candidate volatiles that affect the behavioural response of the malaria mosquito *Anopheles gambiae* sensu stricto to an active kairomone blend: laboratory and semi-field assays. *Physiol. Entomol.* **37**, 60-71.
- Spitzen, J., Smallegange, R. C. and Takken, W.** (2008). Effect of human odours and positioning of CO₂ release point on trap catches of the malaria mosquito *Anopheles gambiae sensu stricto* in an olfactometer. *Physiol. Entomol.* **33**, 116-122.
- StatSoft Inc.** (2007). STATISTICA (data analysis software system), version 8.0. www.statsoft.com.
- Takken, W. and Knols, B. G. J.** (1999). Odor-mediated behavior of Afrotropical malaria mosquitoes. *Annu. Rev. Entomol.* **44**, 131-157.
- Takken, W., van Loon, J. J. A. and Adam, W.** (2001). Inhibition of host-seeking response and olfactory responsiveness in *Anopheles gambiae* following blood feeding. *J. Insect Physiol.* **47**, 303-310.
- Tauxe, G. M., MacWilliam, D., Boyle, S. M., Guda, T. and Ray, A.** (2013). Targeting a dual detector of skin and CO₂ to modify mosquito host seeking. *Cell* **155**, 1365-1379.
- Thom, C., Guerenstein, P. G., Mechaber, W. L. and Hildebrand, J. G.** (2004). Floral CO₂ reveals flower profitability to moths. *J. Chem. Ecol.* **30**, 1285-1288.
- Verhulst, N. O., Andriessen, R., Groenhagen, U., Bukovinszkiné Kiss, G., Schulz, S., Takken, W., van Loon, J. J. A., Schraa, G. and Smallegange, R. C.** (2010). Differential attraction of malaria mosquitoes to volatile blends produced by human skin bacteria. *PLoS ONE* **5**, e15829.
- Webster, B., Lacey, E. S. and Cardé, R. T.** (2015). Waiting with bated breath: opportunistic orientation to human odor in the malaria mosquito, *Anopheles gambiae*, is modulated by minute changes in carbon dioxide concentration. *J. Chem. Ecol.* **41**, 59-66.
- Xia, Y., Wang, G., Buscariollo, D., Pitts, R. J., Wenger, H. and Zwiebel, L. J.** (2008). The molecular and cellular basis of olfactory-driven behavior in *Anopheles gambiae* larvae. *Proc. Natl. Acad. Sci. USA* **105**, 6433-6438.