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Detection of Forest Fires by Smoke and Infrared Reception: the Specialized Sensory Systems of Different "Fire-Loving" Beetles

Waldbranderkennung durch Rauchgas- und Infrarotsensorik: die spezialisierten Sinnesorgane verschiedener "feuerliebender" Käfer

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Summary: "Fire-loving" (pyrophilous) beetles depend on forest fires for their reproduction. Two genera of pyrophilous jewel beetles (Buprestidae) and one species of the genus *Acanthocnemus* (Acanthocnemidae) show a highly pyrophilous behaviour. For the detection of fires and for the orientation on a freshly burnt area these beetles have special sensors for smoke and infrared (IR) radiation. Whereas the olfactory receptors for smoke are located on the antennae, IR receptors are situated on different places on the body of the beetles.

Keywords: pyrophilous beetles, infrared receptor, smoke receptor

Zusammenfassung: "Feuerliebende" (pyrophile) Käfer sind für die Fortpflanzung auf Waldbrände angewiesen. Zwei Gattungen von pyrophilen Prachtkäfern (Buprestidae) und eine Art der Gattung *Acanthocnemus* (Acanthocnemidae) zeigen ein hochgradig pyrophiles Verhalten. Zur Detektion von Waldbränden und zur Orientierung auf frischen Brandflächen besitzen diese Käfer spezielle Sensoren für Rauchgas und Infrarotstrahlung. Während die Geruchsrezeptoren für Rauch auf den Antennen lokalisiert sind, befinden sich die IR-Rezeptoren an unterschiedlichen Stellen auf dem Rumpf der Käfer.

Schlüsselwörter: pyrophile Käfer, Infrarotrezeptor, Rauchgasrezeptor

1. Introduction

Certain species of buprestid beetles show a so-called pyrophilous behaviour; i.e. the beetles approach forest fires (Linsley 1933; Linsley 1943; Evans 1971). Immediately after the blaze, the pyrophilous beetles invade the freshly burnt area where they search for food (e.g. scorched small animals) and start reproduction (Schmitz & Schmitz 2002).
Two genera of jewel beetles (family Buprestidae) can be classified as pyrophilous: About a dozen species of the genus *Melanophila* which are distributed nearly all over the world except Australia and the Australian "fire-beetle" *Merimna atrata* which is endemic to Australia (Poulton 1915; Schmitz & Schmitz 2002). On the freshly burnt area, the males of both genera often stay on the stems of trees close to burning or glowing wood or hot ashes. As soon as they become aware of a conspecific female, they vigorously try to copulate. After mating, the females deposit the eggs under the bark of burnt trees. The reason for the pyrophilous behaviour is that the wood-boring larvae of *Melanophila* and *Merimna* can only develop in the wood of burnt trees (Apel 1989; Schmitz & Schmitz 2002). As a morphological speciality both pyrophilous buprestid genera are equipped with IR receptors (Schmitz & Bleckmann 1997; Schmitz et al. 2001; Schmitz & Trenner 2003).

Another pyrophilous beetle can be found in Australia: the "little ash beetle" *Acanthocnemus nigricans* (family Acanthocnemidae). This inconspicuous beetle is only 4 mm long and highly attracted by hot ashes. However, its biology is unknown. Obviously, *Acanthocnemus* also depends on fires for its reproduction and is equipped with a pair of sophisticated IR receptors (SCHMITZ et al. 2002).
Detecting a fire is, therefore, the compelling precondition for the survival of the pyrophilous beetle species mentioned above. As a consequence, a strong evolutionary pressure has acted upon the sensory systems which enable a beetle to detect and to head for a fire. Additionally, when flying over a burnt area in search for a landing ground, the beetle has to avoid "hot spots" with dangerous surface temperatures above about 55 °C.

2. The smoke detectors

In early reports on the pyrophilous behaviour of *Melanophila* beetles it was postulated that the beetles are attracted by smoke (LINSLEY 1943). 21 years later, behavioural experiments showed that the beetles avoided smoke when tested in an olfactometer (EVANS 1964). Therefore, two questions were still open: (i) can *Melanophila* beetles smell the smoke of burning wood with a sensitivity sufficient to become aware of a remote fire; (ii) do the beetles use olfactory cues to approach a fire.

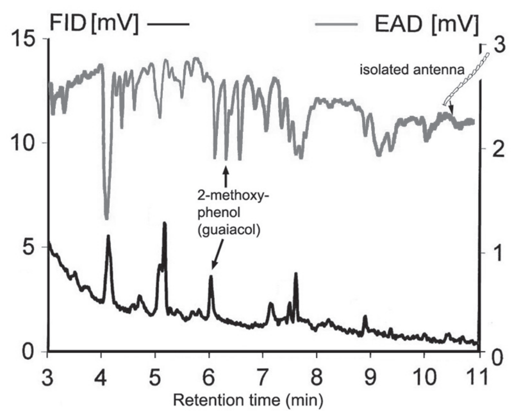

Fig. 1: Gas chromatograms with two detectors: The flame-ionization detector (FID, lower line), indicates any oxidizable compound. An isolated antenna of *Melanophila acuminata* was used as electroantennographic detector (EAD, upper line). The sample contains volatiles released by 1 g of smouldering wood in 1 s, a quantity typically transported over long distances. The FID response indicates quantities of the mixture's components. The EAD response (amplified by a factor of 100) indicates the electrophysiological response of the antenna. 2-methoxyphenol (Guaiacol) elicits the greatest response. The two peaks only in the EAD trace (retention times of 6.0 to 6.5 min) indicates substances detected by the antenna at concentrations below the detection limit of the FID (10 ng per ml of carrier gas). Most probably, they are isomers of 2-methoxyphenol (adapted from SCHÜTZ et al. 1999).

Abb. 1: Gaschromatogramme mit zwei Detektoren: Ein Flammen-Ionisationsdetektor (FID, schwarze Linie) zeigt alle oxidierbaren Substanzen an. Eine isolierte Antenne von *Melanophila acuminata* wurde als elektroantennographischer Detektor (EAD, rote Linie) eingesetzt. Die Probe enthielt Geruchsstoffe, die von 1 g glimmendem Holz in 1 s freigesetzt wurden; eine Menge, die typischerweise über größere Entfernungen transportiert wird. Der FID zeigt die verschiedenen Rauchgasbestandteile an. Das 100-fach verstärkte EAD zeigt die elektrophysiologische Antwort der Antenne auf die einzelnen Rauchgaskomponenten an. 2-Methoxyphenol (Guaiacol) rief die stärkste Antwort hervor. Die beiden Spitzen, die nur in der EAD-Spur auftreten (Retentionszeit zwischen 6 und 6,5 min.) zeigen Substanzen an, die von der Antenne wahrgenommen werden, aber unterhalb der Detektionsschwelle des FIDs liegen (d. h. 10 ng/ml Trägergas). Sehr wahrscheinlich handelt es sich bei diesen Substanzen um Isomere des 2- Methoxyphenols (adaptiert aus SCHÜTZ et al. 1999).

The first question was recently answered by SCHÜTZ and coworkers (SCHÜTZ et al. 1999): It was shown that the isolated antenna of *Melanophila acuminata* can perceive substances emitted in smoke from burning wood. In the experiments volatiles generated by smouldering wood of *Pinus sylvestris* were detected by the antenna with outstanding sensitivity (Fig. 1). Especially derivatives of 2-methoxyphenol (guaiacol), which are released by the incomplete combustion of lignins and, therefore, are very characteristic substances indicating a forest fire, can be perceived with a sensitivity of a few p.p.b. (parts per billion). The authors estimate that this sensitivity is sufficient for the beetles to detect a single pine tree 30 cm in diameter that has smouldering bark to a height of 2 m and a bark depth of 1 cm, releasing about 7 g of guaiacol in an hour under light wind conditions from a distance of 1 km. Therefore, it is very probable that beetles of the genus *Melanophila* become aware of a fire by olfactory cues. Our current hypothesis is that the beetles smelling smoke take off in search for the fire. Whether they use olfaction to approach the fire (see the second of the above question) has to be examined.

Until now, no published results of a similar sensitivity for smoke in *M. atrata* are available. However, first investigations have shown that the antenna of *Merimna* is also very sensitive to components contained in the smoke of burning eucalyptus wood (SCHÜTZ pers. communication). Compared to the conditions found on the antenna in other buprestid beetles, the antenna of *M. atrata* is characterized by sensilla which have very short pegs (SCHMITZ unpublished observations, Fig. 2A). Long and thin-walled olfactory sensilla are highly endangered by drying out at high ambient temperatures. Therefore, this feature can be interpreted as a special adaptation to the high temperature environment encountered by the beetles near open fires.

3. The infrared receptors

As already mentioned, all pyrophilous beetles show special IR receptors. Because the pyrophilous behaviour of *Melanophila* species and *M. atrata* is almost identical, one may speculate that IR receptors are also built in the same way. However, the IR receptors in the two genera are totally different!

In *Merimna atrata* two pairs of abdominal IR receptor can be found ventrolaterally on the second and third abdominal sternite (Fig. 3A). Each receptor consists of a more or less round IR absorbing area which is slightly sunken into the surrounding cuticle (Fig. 2B). Insect cuticle per se is a strong absorber for IR radiation around about 3 μm which corresponds to the maximum of emission of a forest fire (VONDRAN et al. 1995). In addition, the honeycomb like microstructure of the absorbing area may enhance absorption. As a result, an increase in temperature will occur. This increase is measured by a large thermosensitive multipolar neuron which is attached to the cuticle of the absorbing area from inside. A striking feature of this multipolar neuron is its dendritic region: several hundred small terminal dendrites which are densely filled with mitochondria are packed together and forming a compact terminal dendritic mass (TDM) (Fig. 2C). In principle, the stimulus perceiving dendritic structures show the same construction design as the terminal nerve masses (TNMs) of the thermosensitive trigeminal nerve fibres which innervate the IR receptors in IR sensitive snakes (in boid snakes e.g. pythons and in crotalid snakes e.g. rattlesnake) (BULLOCK & FOX 1957; TERASHIMA et al. 1970; VON DÜRING 1974). Like the IR receptors in those snakes, the IR receptors of *M. atrata* can also be classified as microbolometers. Electrophysiological recordings from the *M. atrata* IR receptors have shown, that the receptors are not very sensitive (SCHMITZ & TRENNER 2003). Therefore, it can be postulated that *Merimna* may use its receptors in the near range to prevent to land on a hot surface.

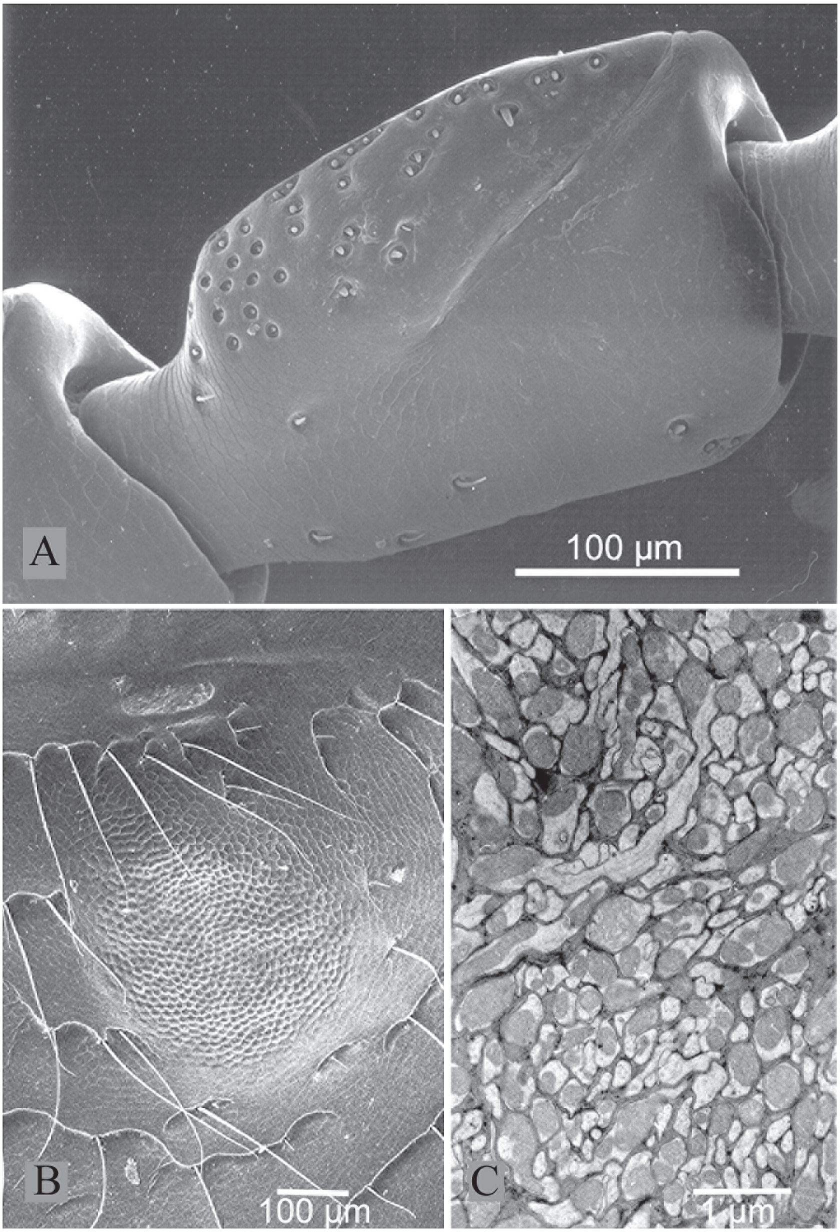

Fig. 2 A-C: A SEM image of an antennomer of *Merimna atrata*. Note that the sensilla are all short-peged. **B** IR receptor of *Merimna atrata*: SEM image of the absorbing surface on the second sternite. **C** Cross section through terminal dendritic mass (TDM). Dark Glial cells ensheath and interconnect the dendrites. Note that in nearly every cross section of a dendrite a mitochondrium is located.
Abb. 2 A-C: A Rasterelektronenmikroskopsiches (REM) Bild eines Antennengliedes von *Merimna atrata*. Alle Sensillen weisen nur sehr kurze Borsten auf. **B** IR-Rezeptor von *Merimna atrata*: REM Bild der absorbierenden Fläche auf dem 2. Sternit. **C** Querschnitt durch die terminale Dendritenmasse (TDM). Dunkle Gliazellen umhüllen und verbinden die Dendriten. In nahezu jedem Dendritenquerschnitt befindet sich ein Mitochondrium.

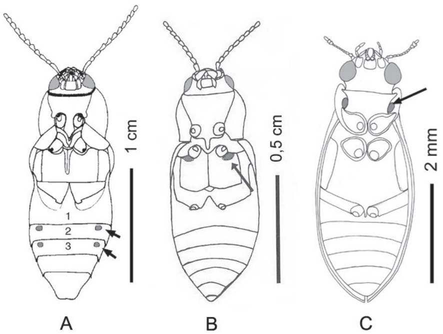

Fig. 3 A-C: Schematic drawings of (**A**) *Merimna atrata*, (**B**) *Melanophila acuminata*, and (**C**) *Acanthocnemus nigricans*. Beetles are shown from their ventral side (legs omitted). Arrows point to the IR receptors.
Abb. 3 A-C: Schematische Zeichnung von (**A**) *Merimna atrata*, (**B**) *Melanophila acuminata* und (**C**) *Acanthocnemus nigricans*. Die Käfer sind von der Ventralseite gezeigt (Beine entfernt). Die Pfeile zeigen auf die IR-Rezeptoren.

In *Melanophila* beetles, two pairs of metathoracic pit organs can be found directly behind the coxae of the middle legs (Fig. 3B). Each pit organ houses about 70 cuticular sensilla (Fig. 4A) which most probably have evolved from hair mechanoreceptors (sensilla trichoidea, VONDRAN et al. 1995). In contrast to the IR receptors of *Merimna atrata*, morphological as well as physiological investigations have revealed that the cuticular apparatus of each sensillum (i.e. the little spherule) is innervated by a ciliary mechanoreceptor. Therefore, not the increase of temperature but the expansion of the spherule due to IR absorption is measured. This has been called the photomechanic principle of IR detection (SCHMITZ & BLECKMANN 1998). The physiological and behavioural data available so far suggest that *Melanophila* beetles may use their IR receptor for the detection of remote fires (EVANS 1964; VONDRAN et al. 1995; SCHMITZ & TRENNER 2003).

Last but not least, the "little ash beetle" *Acanthocnemus nigricans* which does not belong to the family of Buprestidae but is classified into the superfamily of the Cleroidea, has one pair of IR receptors on both sides of the prothorax which are situated just anterior to the coxae of the prothoracic legs (Fig. 3C). The main component of an IR organ is a cuticular "sensory disc" which is situated over an air-filled cavity (Fig. 4C). About 70 cuticular sensilla were found on the outer surface of the disc. The cone shaped cuticular peg of a sensillum is 1-3 μm long and about 2 μm in diameter. The peg has no pores and is surrounded by a cuticular wall (inset in Fig. 4C). The single sensory cell of the sensillum shows some similarities to a mechanoreceptive sensory cell of a trichoid sensillum. However, three specializations can be found: (i) the dendritic outer segment is enveloped by a pronounced electron-dense structure, which most likely represents the hypertrophied dendritic sheath of the outer dendritic segment. (ii) the membranes of the dendritic inner segment and the soma show distinct infoldings which contain a high amount of mitochondria. These structures show analogies to the dendritic endings of the thermoreceptive sensory cells innervating IR receptors in snakes (BLEICHMAR & DE ROBERTIS 1962; MOLENAAR 1992; AMEMIYA et al. 1996) and in *Merimna atrata* (iii) no tubular body can be found. As this specialized new type of insect sensillum is the only sensory system within the disc, it can be postulated that it is responsible for the response of the organ to infrared radiation and may act as a thermoreceptor. Further examinations will have to test this hypothesis.

4. Summary and conclusions

Finding a forest fire is a crucial task for the introduced pyrophilous beetles. Forest fires occur totally unpredictably. Therefore, a strong evolutionary pressure has acted upon the sensory systems of the beetles enabling them to detect a fire from distances as large as possible. Forest fires emit light, noise, smoke and infrared (IR) radiation. Up to now, there is no evidence that pyrophilous beetles use

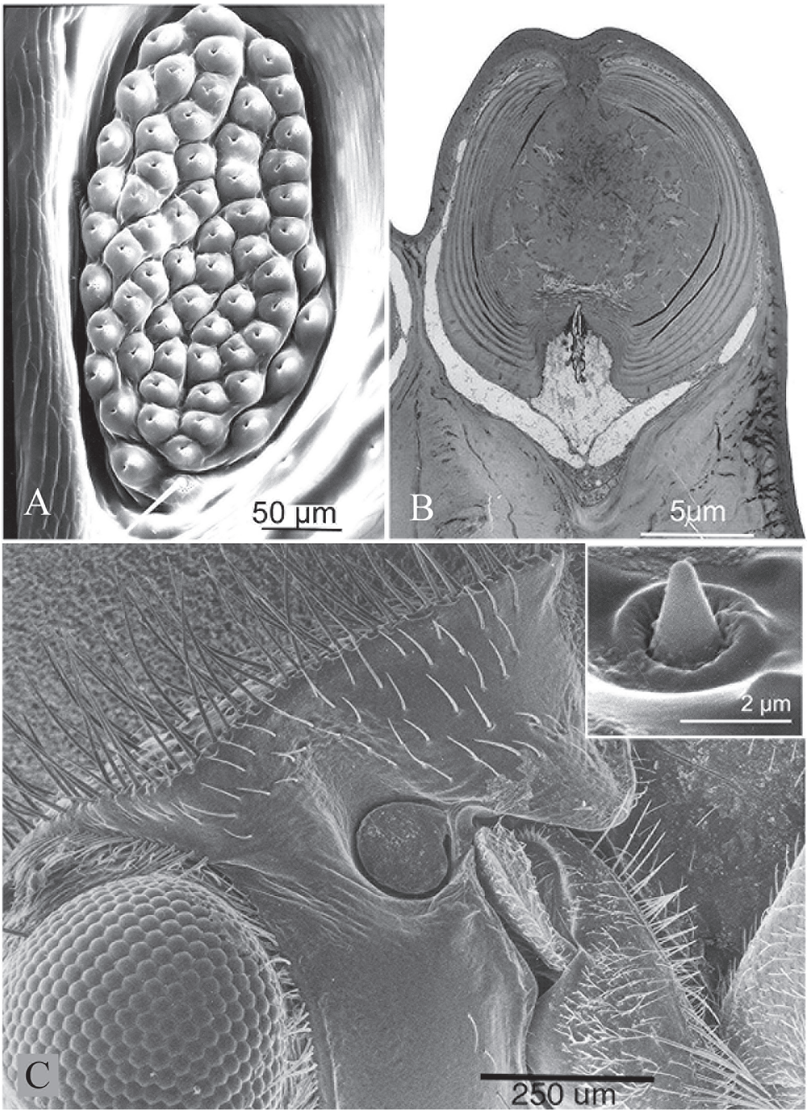

Fig. 4 A-C: IR receptor of *Melanophila acuminata.* **A** SEM image of IR pit organ with IR sensilla. **B** Section through a single sensillum. Under the outer cuticle which bulges out hemispherically, a massive cuticular sphere is located. The sphere is innervated from below by a single dendrite of a mechanoreceptor. **C** Lateral view of the prothorax of *Acanthocnemus nigricans*. The IR receptor is located anteriorly to the coxae of the prothoracic leg. The sensory disc situated over an air-filled cavity can be seen. Inset: Single sensillum which can be found on the outer surface of the sensory disc.

Abb. 4 A-C: IR-Rezeptor von *Melanophila acuminata*. **A** REM Bild des IR Grubenorgans mit den Sensillen. **B** Schnitt durch ein einzelnes Sensillum. Unterhalb der sich halbkugelförmig aufwölbenden äußeren Kutikula befindet sich eine massive Kutikulakugel. Die Kugel wird von unten durch einen einzelnen Dendriten eines Mechanorezeptors innerviert. **C** Seitenansicht des Prothorax von *Acanthocnemus nigricans*. Der IR-Rezeptor befindet sich vor den Coxen der Vorderbeine. Die sensorische Scheibe ist über einer luftgefüllten Grube angeordnet. Inset: Einzelnes Sensillum der Außenfläche der sensorischen Scheibe.

visible light or sound for the detection and localization of forest fires. A typical forest fire burns with a temperature of about 500 to 1000 °C. Fires of this temperature which also emit enormous amounts of smoke, have a maximum of emission of electromagnetic radiation in the infrared (IR) wavelength range 2.2 to 4 μm. Since IR radiation with this wavelength is transmitted well through an atmospheric window, IR reception and the smell of burning wood are useful tools for the detection and localization of burning trees. As shown for *Melanophila acuminata*, certain antennal olfactory receptors have developed into specialized sensors for the detection of characteristic compounds in smoke. The following hypothetical scenario could explain the evolutionary pathway towards IR organs. Insect cuticle absorbs IR radiation very well (VONDRAN et al. 1995) and this causes heating of the underlying tissue. At a certain temperature, heating may have irritated some sensilla and internal neurones of the body wall. If these "unphysiological" excitations became combined with reactions which are meaningful in the behavioural context of a pyrophilous insect, a selective pressure for evolutionary transformation became effective. A greater sensitivity seems desirable because it is of advantage to detect an IR source from greater distances. Consequently, the sites on the integument with the best prerequisite of evolving into an IR organ were those in a ventrolateral position facing the ground as well as the lateral environment of the flying beetle. The result was a synorganization of the corresponding part of the cuticle, the epidermis, and the underlying nervous system (in case of *Merimna atrata* the chordotonal organs and the multipolar neuron).

References

AMEMIYA, F., USHIKI, T., GORIS, R. C., ATOBE, Y., & KUSUNOKI, T. (1996): Ultrastructure of the crotaline snake infrared receptors: SEM confirmation of TEM findings. Anatomical Record 246:135-146.

APEL, K.-H. (1989): Zur Verbreitung von *Melanophila acuminata* DEG. (Col., Buprestidae). Entomologische Nachrichten und Berichte 33: 278-280.

BLEICHMAR, H., & DE ROBERTIS, E. (1962): Submicroscopic morphology of the infrared receptor of pit vipers. Zeitschrift für Zellforschung und Mikroskopische Anatomie 56: 748-761.

BULLOCK, T. H., & FOX, W. (1957): The anatomy of the infrared sense organ in the facial pit of pit vipers. Quarterly Journal of Microscopical Science 98: 219-234.

EVANS, W. G. (1964): Infrared receptors in *Melanophila acuminata* De Geer. Nature 202: 211.

EVANS, W. G. (1971): The attraction of insects to forest fires. S. 115-127 in: Proceedings of the Tall Timbers Conference on Ecological Animal Control by Habitat Management No. 3. The Station Publishers; Tallahassee, Florida.

LINSLEY, E. G. (1933): Some observations on the swarming of *Melanophila*. Pan-Pacific Entomologist 9:138.

LINSLEY, E. G. (1943): Attraction of *Melanophila* beetles by fire and smoke. Journal of Economical Entomology 36: 341-342.

MOLENAAR, G. J. (1992): Anatomy and physiology of infrared sensitivity of snakes. S. 368-453 in: GANS, C. (ed.): Biology of the Reptilia, Vol. 17. University of Chicago Press; Chicago.

POULTON, E. B. (1915): The habits of the Australian buprestid "fire-beetle" *Merimna atrata*. Transactions of the Entomological Society London Pt. 1, Proceedings, 3-4.

SCHMITZ, H., & BLECKMANN, H. (1997): Fine structure and physiology of the infrared receptor of beetles belonging to the genus *Melanophila* (Coleoptera: Buprestidae). International Journal of Insect Morphology & Embryology 26: 205-215.

SCHMITZ, H., & BLECKMANN, H. (1998): The photomechanic infrared receptor for the detection of forest fires in the buprestid beetle *Melanophila acuminata*. Journal of Comparative Physiology A 182: 647-657.

SCHMITZ, H., & SCHMITZ, A. (2002): Australian fire-beetles. Landscope, Spring 2002: 36-41.

SCHMITZ, H., SCHMITZ, A., & BLECKMANN, H. (2001): Morphology of a thermosensitive multipolar neuron in the infrared organ of *Merimna atrata* (Coleoptera, Buprestidae). Arthropod Structure & Development 30: 99-111.

SCHMITZ, H., SCHMITZ, H., TRENNER, S., & BLECKMANN, H. (2002): A new type of insect infrared organ of low thermal mass. Naturwissenschaften 89: 226-229.

SCHMITZ, H., & TRENNER, S. (2003): Electrophysiological characterizatin of the multipolar thermoreceptors in the „fire-beetle" *Merimna atrata* and comparison with the infared sensilla of *Melanophila acuminata* (both Coleoptera, Buprestidae). Journal of Comparative Physiology A 189: 715-722.

SCHÜTZ, S., WEISSBECKER, B., HUMMEL, H. E., APEL, K.-H., SCHMITZ, H., & BLECKMANN , H. (1999): Insect antennae as a smoke detector. Nature 398: 298-299.

TERASHIMA, S., GORIS, R. C., & KATSUKI, Y. (1970): Structure of warm fiber terminals in the pit membrane of vipers. Journal of Ultrastructure Research 31: 494-506.

VON DÜRING, M. (1974): The radiant heat receptor and other tissue receptors in the scales of the upper Jaw of *Boa constrictor*. Zeitschrift für Anatomie und Entwicklungsgeschichte 145: 299-319.

VONDRAN, T., APEL, K.-H., & SCHMITZ, H. (1995): The infrared receptor of *Melanophila acuminata* De Geer (Coleoptera: Buprestidae): ultrastructural study of a unique insect thermoreceptor and its possible descent from a hair mechanoreceptor. Tissue & Cell 27: 645-658.

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