

- 99 Sulzman, F. M., Fuller, C. A., and Moore-Ede, M. C., Effects of phasic and tonic light inputs on the circadian organization of the squirrel monkey. *Photochem. Photobiol.* 34 (1981) 249–256.
- 100 Takahashi, J. S., and Menaker, M., Role of the suprachiasmatic nuclei in the circadian system of the house sparrow, *Passer domesticus*. *J. Neurosci.* 2 (1982) 815–828.
- 101 Takahashi, J. S., and Menaker, M., Entrainment of the circadian system of the house sparrow: a population of oscillators in pinealectomized birds. *J. comp. Physiol. (A)* 146 (1982) 245–253.
- 102 Takahashi, J. S., and Menaker, M., Multiple redundant circadian oscillators within the isolated avian pineal gland. *J. comp. Physiol. (A)* 154 (1984) 435–440.
- 103 Takahashi, J. S., and Zatz, M., Regulation of circadian rhythmicity. *Science* 217 (1982) 1104–1111.
- 104 Turek, F. W., Are the suprachiasmatic nuclei the location of the biological clock in mammals? *Nature* 292 (1981) 289–290.
- 105 Vernikos-Danellis, J., and Winget, C. M., The importance of light, postural and social cues in the regulation of the plasma cortisol rhythm in man, in: *Advances Bioscience*, 19, *Chronopharmacology*, pp. 101–106. Eds A. Reinberg and F. Halberg. Pergamon, Oxford 1979.
- 106 Weitzman, E. D., Czeisler, C. A., and Moore-Ede, M. C., Sleep-wake, neuroendocrine and body temperature circadian rhythms under entrained and non-entrained (free-running) conditions in man, in: *Biological Rhythms and their Central Mechanism*, pp. 199–227. Eds M. Suda, O. Hayaishi and H. Nakagawa. Elsevier, North-Holland, New York 1979.
- 107 Weitzman, E. D., Zimmerman, J. C., Czeisler, C. A., and Ronda, J., Cortisol secretion is inhibited during sleep in normal man. *J. clin. Endocr. Metab.* 56 (1983) 352–358.
- 108 Wever, R. A., *The Circadian System of Man: Results of Experiments under Temporal Isolation*. Springer-Verlag, New York 1979.
- 109 Wever, R. A., On varying work-sleep schedules, in: *Biological Rhythms, Sleep and Shift Work*, pp. 35–60. Eds L. C. Johnson, D. I. Tepas, W. P. Colquhoun and M. H. Colligan. Spectrum, New York 1981.
- 110 Wever, R. A., Behavioural aspects of circadian rhythmicity, in: *Rhythmic Aspects of Behaviour*, pp. 105–171. Eds F. M. Brown, R. C. Graeber, Lawrence Erlbaum, London 1982.
- 111 Wever, R. A., Influence of physical workload on free-running circadian rhythms of man. *Pflügers Arch.* 381 (1979) 119–126.
- 112 Wever, R. A., Fractional desynchronization of human circadian rhythms. A method for evaluating entrainment limits and functional interdependencies. *Pflügers Arch.* 396 (1983) 128–137.
- 113 Wever, R. A., Toward a mathematical model of circadian rhythmicity, in: *Mathematical Models of the Circadian Sleep-Wake Cycle*, pp. 17–77. Eds M. C. Moore-Ede and C. A. Czeisler. Raven Press, New York 1984.
- 114 Wever, R. A., Sex differences in human circadian rhythms: intrinsic periods and sleep fractions. *Experientia* 40 (1984) 1226–1234.
- 115 Wever, R. A., Polasek, J., and Wildgruber, C. M., Bright light affects human circadian rhythms. *Pflügers Arch.* 396 (1983) 85–87.
- 116 Wiedemann, G., Splitting in a circadian activity rhythm: the expression of bilaterally paired oscillators. *J. comp. Physiol. (A)* 150 (1983) 51–60.
- 117 Winfree, A. T., Circadian timing of sleepiness in man and woman. *Am. J. Physiol.* 243 (1982) R193–R204.
- 118 Winfree, A. T., Impact of a circadian clock on the timing of human sleep. *Am. J. Physiol.* 245 (1983) R497–R504.
- 119 Winfree, A. T., Exploratory data analysis: published records of uncued human sleep-wake cycles, in: *Mathematical Models of the Circadian Sleep-Wake Cycle*, pp. 187–199. Eds M. C. Moore-Ede and C. A. Czeisler. Raven Press, New York 1984.
- 120 Zulley, J., Wever, R. A., and Aschoff, J., The dependence of onset and duration of sleep on the circadian rhythm of rectal temperature. *Pflügers Arch.* 391 (1981) 314–318.

0014-4754/86/010001-13\$1.50 + 0.20/0

© Birkhäuser Verlag Basel, 1986

Sensitivity variations in insect chemoreceptors; a review¹

W. M. Blaney², L. M. Schoonhoven³ and M. S. J. Simmonds⁴
Behavioral Entomology Group, Department of Zoology, Birkbeck College, Malet Street, London WC1E 7HX (England)

Key words. Insects; chemoreceptor; receptor sensitivity; feeding behavior; central regulating mechanisms; peripheral regulating mechanisms; sensory behavior.

Introduction

The feeding behavior of insects, like that of other animals, depends heavily on neural input from their chemical senses. Therefore the chemoreceptors of insects have attracted much interest and the gustatory sense of blowflies, and to a lesser extent of lepidopterous larvae, are among the best studied chemoreceptor systems in the invertebrates^{23, 60}. These studies have concentrated on determining receptor specificities and sensitivities, with the aim of elucidating the neural code which governs food selection behavior. Concomitant observations on the structure of chemoreceptors have revealed their micro-architecture⁷⁶. Since there is no unequivocal evidence for the existence of efferent neural control of insect chemoreceptors, most studies on the relationships between sensory input and insect behavior assume receptor activity to be solely dependent on stimulus characteristics. A grow-

ing number of reports, however, indicate that receptor sensitivity may vary depending on developmental stage, feeding history and/or physiological state of the insect. Such peripheral neural changes and the processes which regulate them are the subject of this review.

Changes in receptor characteristics

Inconstancies in sensory input to the central nervous system (cns) under standardized stimulus conditions may be due to either changes in the accessibility of the receptors to the stimulus or to sensitivity changes in the receptors per se. The gustatory pegs on the palps of locusts exemplify sensilla which become unresponsive to chemicals after the insect has finished a meal, due to the closure of their distal orifices⁹. Some reports in the literature suggest that in flies and caterpillars also, a partial con-

striction of the apical pore in contact chemoreceptors may be responsible for a temporary reduction of receptor activity^{44, 72, 75}. Besides this physical barrier, which may produce modulations of sensory input, instances are known in which the chemoreceptor cells themselves may vary in sensitivity, as measured by a change in firing rate in response to a given concentration of stimulus. In some olfactory^{21, 50} and gustatory^{47, 69} sensilla several or all receptor cell types within a single sensillum may change their sensitivity. In other cases not all receptors of a sensillum alter their sensitivity concurrently, but only one or more particular cells show such changes^{15, 57, 65}.

The changes in sensitivity described are a function of the insect's previous experience or its developmental stage. As in all physiological processes, the temporal characteristics of the sensitivity changes in chemoreceptors are of fundamental importance. It should be mentioned here that the phenomenon to be discussed differs from the well-known sensory adaptation in its time scale. Whereas the duration of normal chemosensory adaptation and disadaptation is in the range of seconds to minutes, the sensitivity changes dealt with here may require hours to weeks to develop. The time courses involved have received attention only in a few cases. The lactic acid receptor in mosquito antennae shows a maximum change two days after a blood meal. A return to prefeeding sensitivity levels, which follows the oviposition act, likewise takes one to two days^{19, 21}. When tobacco hornworm larvae are exposed for two and a half days to an artificial diet containing salicin, a compound which stimulates the feeding 'deterrent' receptor, the sensitivity of this taste cell is lowered markedly. The reduction can be further increased by even longer exposures⁵⁷. Addition of allelochemicals such as azadirachtin, nicotine or sinigrin for two days to the artificial diet of *Spodoptera* spp. larvae suffices to evoke a strong reduction in their receptor responses to these compounds^{12, 65}. When blowflies are deprived of food for periods of 1–2 days their labellar sensilla show considerable increases in receptor sensitivities⁴⁸. Although experiments have generally not monitored the time course of changes in receptor sensitivity, it appears from the cases cited that periods of 1–2 days are needed to change chemosensory responses. Probably comparable periods are required for reverse reactions^{19, 48, 57}.

Time related changes in receptor sensitivity

Changes in receptor sensitivity often show a direct relationship to time, like aging processes, or are linked to factors or processes which normally have a regular time pattern, such as light-dark cycles, temperature cycles or reproductive cycles.

In several instances, age has been found to have an effect on the sensitivity level of chemoreceptors in adult insects. Thus, in newly emerged mosquitos the receptors which perceive host odors are inactive, and the insects do not feed. Some days elapse before the receptors become functional and feeding may begin²⁰. By contrast, the taste sensilla of blowflies become responsive three days before emergence³⁸. Fully functional receptors may also vary with age. The amplitudes of electroantennograms, which represent the summed receptor potentials from antennal olfactory cells, become larger with increasing age in

moths of the spruce budworm^{50, 55} and some other lepidopterans^{34, 63}. Conversely, sensory input to the CNS may decline with aging. In male blowflies, for example, the number of inoperative sensilla increases gradually and reaches a level of more than 50% after 25 days⁵³. The sensitivity of the receptors for sugar and salt in those sensilla which remain operative also reduces with age⁵³. Curiously, the chances of becoming inoperative due to aging vary with the position of the sensilla. Hairs at the front of the labellum are increasingly affected by age, whereas the hairs at the back of this organ are not⁷¹. Similarly, changes in receptor sensitivity can occur during the course of individual instars in immature insects. Thus the responses of two gustatory receptors in fifth instar tobacco hornworms reach a maximum during the mid-instar stage⁵⁸. In *Spodoptera exempta* the adenosine receptor becomes gradually more sensitive during the last larval instar, though some other receptors remain unchanged^{12, 17}. When different larval instars are compared, the sensitivity of certain receptors increases over the last three instars in *Spodoptera exempta*, *S. littoralis* and *Heliothis virescens*¹². Thus age may influence chemoreceptor sensitivity in different ways in different insect species, and in different ontogenetic phases.

Cyclic fluctuations in receptor sensitivity have been reported in association with changing internal and external factors. For example, in females of the blowfly *Calliphora vomitoria* such variations occur synchronously with ovarian cycles, suggesting that both phenomena are controlled by the same mechanism⁷. Increased sensitivity to salt occurred at the beginning of vitellogenesis, which is triggered by release of juvenile hormone (JH) into the hemolymph. A similar change occurs in mosquitos following a blood meal, which initiates vitellogenesis; the observed decline in sensitivity of receptors responsive to host odors, and increased sensitivity of receptors responsive to oviposition site attractants, could be induced in non-blood-fed females by transfusion of hemolymph from blood-fed females²¹. The finding by Stoffolano⁶⁹ that sensitivity changes in sugar receptors of blowflies vary according to sex, whereas the changes found in salt cells are independent of sex, is probably also related to metabolic differences associated with reproductive functions.

Reproduction and feeding activities often take place at certain times of the day or the night, and one might therefore expect to find that amongst receptors associated with these activities, any which had modifiable sensitivity levels would show circadian changes in sensitivity. During the ultimate larval instar of *Spodoptera exempta* and *S. littoralis* there was found to be reduced sensitivity of maxillary styloconic receptors to 0.05 M sucrose during the dark phase of the daily cycle, compared with the light phase¹². The fact that adult houseflies after sustained exposure (3–6 days) to darkness show strongly reduced chemosensory responses to sucrose as compared to flies kept under normal light patterns⁴⁸ may be indicative of their sensitivity to light regimes. Occasionally infradian rhythms associated with feeding have been reported, e.g. in locusts⁶⁶. Whether this is accompanied by synchronous changes in receptor sensitivity is not known. However, it has been shown in locusts that accessibility of the receptors changes, due to closure of the tips of the

maxillary palp sensilla, immediately after a meal⁹. In *Phormia regina* Rachman⁵² noticed the existence of large fluctuations in latency from the onset of receptor stimulation to the first sugar spike, and remarked that these fluctuations may have a circadian component. By contrast, Hall³⁰, studying the circadian rhythm of proboscis extension responsiveness on stimulation of the tarsi with sucrose, found no daily change in the sensitivity of the tarsal receptors.

Many insects enter a state of diapause in response to specific light-dark cycles. Blowflies, *Phormia regina*, have during their facultative diapause an elevated threshold for the behavioral response of feeding when the tarsi are stimulated with sugar⁷⁰. Corresponding electrophysiological data on the tarsal sugar receptors are not available, but Stoffolano has investigated labellar receptors, which also mediate feeding in diapausing and active flies. The sensitivity, as measured by firing frequency in response to 0.5 M sucrose, did not differ between the two groups but the number of inoperative sensilla in the diapausing flies was nearly double that in the non-diapausing group^{69,70}. Likewise, the maxillary receptors of larvae of *Dendrolimus pini* do not show changes in their neural responses to chemicals after entering an obligatory diapause during which they do not feed⁶¹. Thus, the extent to which inhibition of feeding during diapause is mediated by central or peripheral factors is still uncertain.

The existence of changes in receptor sensitivity in relation to age seems to be well established; there is less evidence for the occurrence of cyclic sensitivity fluctuations.

Changes in receptor sensitivity related to feeding history

Feeding behavior involves aspects both of quantity and of quality. Although these elements are often difficult to separate completely from each other, they present a useful classification for discussing the literature on the effects of food uptake and food quality on receptor sensitivity. First, we shall consider the effects of quantity of food intake.

The closure of the distal pores, seen in the palp-tip sensilla of locusts immediately after a meal, is correlated with distension of the crop. This is concluded from the observation that filling the crop with an inert substance like agar, provokes the closing reaction⁸. Obviously this mechanism affects the sensory input received by the CNS because the accessibility of the receptors is reduced, although the responsiveness of the receptor cells is not altered⁹. In blowflies, on the other hand, the excitability of the receptor cells gradually increases when the insects are deprived of food for 24–48 h or longer. The sugar receptor is particularly affected by fasting or feeding whereas the water receptor is less affected^{47,48}. As in the locust, it is the amount of food ingested which determines the receptor reaction, rather than its nutritional quality. Thus, in the blowfly ingestion of a non-nutritive sugar solution (D-arabinose) evokes the same changes in receptor sensitivities as ingestion of sugars which can be metabolized⁴⁷. In the locust experiments, the insects did not taste or ingest the material injected into the crop, whereas with the flies, both tasting and ingesting were involved. Nevertheless, in both cases it may be inferred that some central mechanism is responsible for the peripheral

changes. However, unlike Omand⁴⁷, Rachman⁵² did not find an effect of feeding on receptor responses in an experiment in which each fly served as its own control. The experimental conditions in the two studies, however, differed, Omand used flies which were allowed to move freely and, during feeding periods, had free access to food^{47,48}. Rachman on the other hand used flies which were physically restrained from moving. They were fed (with food or water) once a day with a fluid quantity filling their crops only to about 50% capacity⁵². Moreover, Rachman⁵² followed the effects of food deprivation on sensory responses of individual flies during 24-h periods only, whereas Omand⁴⁷ monitored sensitivity changes over 2 days or more in populations of flies. Thus, there are not adequate grounds for asserting that the conclusions reached by Omand have been invalidated by Rachman's results. Another short time scale study on tarsal receptors of blowflies, in which neural responses immediately before a meal and 1 h later were compared, did not reveal any differences²⁹. In larvae of *Pieris brassicae* a starvation period of 24 h did not alter the sensitivity of their sugar receptors¹⁵.

An example of olfactory receptors changing their sensitivity in relation to feeding is found in female mosquitos. One to two days after a blood meal the sensitivity of lactic acid receptors, responding to host odors, is reduced. Interestingly, at the same time, receptors tuned to oviposition site attractants (e.g. methyl butyrate), show an increase in sensitivity. After oviposition the sensitivity of the lactic acid-excited neurons increases again. The synchronous alterations in both receptor types are probably evoked by a common hemolymph-borne factor²¹. Food quality has also been found in some instances to affect receptor sensitivities. When tobacco hornworms are grown on an artificial diet the responses of their maxillary taste sensilla to leaf saps of various plants are different as compared to plantgrown insects⁵⁶. When reared on two different host plant species sensory responses to the saps of those plants also differ⁶⁸. The question arises whether all receptors have changed as a result of raising the insects on different foods, or only some of them. When larvae grown on an artificial diet are compared to larvae grown on a host plant, it appears that several receptor types are affected, though not all. Whereas the inositol receptor in diet-reared larvae becomes more than 2½ times as sensitive as in plant-reared larvae, the sugar receptor is unaffected⁵⁷. By adding inositol or salicin to the artificial diets, a reduction of sensitivity is induced in the receptors tuned to inositol or salicin respectively^{57,58}. Likewise the addition of azadirachtin, an allelochemic deterrent to *Spodoptera exempta* and *S. litoralis*, to an artificial diet for a period of two days reduces the sensitivity of their deterrent receptors, whereas their sugar-sensitive receptors remain unaltered⁶⁵.

The deterrent receptor in *Pieris rapae* shows a somewhat lowered responsiveness to strychnine when the larvae are reared on cabbage leaves which were sprayed with this chemical, compared to larvae reared on untreated leaves⁴⁴. Stoffolano⁶⁹ describes the influence of food quality on receptor sensitivity in adults of the blowfly, *Phormia regina*. Diapausing female flies which were fed sugar and liver showed a reduced sensitivity of their salt and sugar receptors as compared to flies which were fed sugar

only. Also their number of operative sensilla had decreased⁶⁹.

The examples given warrant the conclusion that, within a meal, the quantity and, over a period, the quality of food can affect the sensitivity of peripheral chemoreceptors, involved in feeding behavior.

Regulatory mechanisms

The regulation of receptor responsiveness may have two aspects, namely a central mechanism which feeds back on the receptors, or a mechanism localized at the receptor cell level, which, in response to some central signal or to a peripheral factor, adjusts the receptor sensitivity. First we will discuss centrally controlled processes and then regulating processes occurring at the peripheral level.

Central regulating mechanisms

Central regulation processes in animals involve primarily endocrine and neural pathways. Indeed it has been suggested that both may take part in the regulation of receptor sensitivity, though the evidence for the latter is limited. In vertebrates, chemoreceptor sensitivity is affected by centrifugal neural control^{32,34}. It is generally assumed that chemoreceptors in arthropods are not subject to efferent neural control. However, there is some morphological evidence for the presence of efferent innervation of some gustatory receptors in a cockroach⁴⁵, and in an ultrastructural study of mouthpart chemoreceptors in the migratory locust, Cook¹⁸ shows isolated axons of unknown origin in close proximity to receptor neurons. Obviously efferent neural control would allow different receptor types to be regulated independently. The influence of hormones, directly or indirectly, on the functioning of insect chemoreceptors, has been indicated by a number of studies. Bernays and Chapman⁸ showed that feeding in locusts, by way of foregut distention, stimulates hormone release from the corpora cardiaca. Increasing titer of this hormone in the hemolymph is correlated with activation of the closing mechanism of the palp-tip sensilla, so that the receptors temporarily become inaccessible to outside chemical stimuli⁹.

It has also been suggested that in insects other than locusts the size of the sensillum pore may vary somewhat, and thereby control within a certain range the responsiveness of the receptors. Morphological evidence for variations of pore size is available for blowfly receptors^{73,75}. These changes are accompanied by changes in electrical resistance. Angioy et al.⁷ have suggested that the cyclic variation of electrical resistance (and concomitant variation in spike activity) is controlled by the same endocrine factor which regulates ovarian function. The fact that large fluctuations occur in latency from the onset of stimulation to the first sugar spike in fly sensilla is also indicative of some type of regulation of the accessibility of the receptor membrane⁵². In lepidopterous larvae occasional sudden increases in spike frequencies and a concomitant increase in amplitudes have been found to occur during an electrophysiological recording, which may indicate a change in pore size⁶¹. Although the evidence for the existence of a mechanism regulating pore size, and thereby

receptor accessibility in blowflies and lepidopterous larvae, is suggestive, this phenomenon cannot as yet be considered to be proven beyond doubt.

When one or more hormones affect receptor sensitivity this could occur either directly or via some intermediate process. Hodgson³³ reported that the presence of epinephrine (which mimics certain effects of corpora cardiaca extracts) or dopamine (which occurs in the insect CNS) in the stimulating solutions strongly stimulates the salt receptor in blowflies and suggests that there is some degree of lability of the response which may be directly influenced by the hormonal milieu of the taste cells. Exogenously applied ecdysteroids have also been found to stimulate arthropod (crustacean) chemoreceptors⁶⁷.

Hormonal effects on chemoreceptors might additionally, or alternatively, be exerted indirectly via hemolymph composition and/or changes in the dendritic liquor. Phillips and Vande Berg⁵¹ have demonstrated the existence of a mechanism for transporting materials from the hemolymph into the sensillum cavity and Jachmann et al.³⁵ found a correlation between the ionic composition of the hemolymph in blowflies and the sensitivity of two receptor cell types. Clearly, if the dendritic liquor in some way reflects hemolymph ionic composition, this most probably would affect receptor characteristics¹⁶. Furthermore, Küppers and Thurm^{39,39a} observed that 5-hydroxytryptamine stimulated the transport of K⁺ ions from the hemolymph to the dendritic liquor, thus raising the transepithelial potential by 20–25%. Conceivably such changes in the transepithelial potential parallel concomitant changes in receptor resting potential, thereby altering receptor sensitivity. On the basis of the evidence available now, the following hypothesis may be tenable. One or more hormones effect ion transport processes in the tormogen cells and thus control the ionic composition of the dendritic liquor, which in its turn influences receptor sensitivity. Although there is good evidence that juvenile hormone (JH) can change the sensitivity of chemoreceptors, the direction in which the sensitivity is reported to change is not consistent. It is believed that JH controls both chemoreceptor sensitivity and ovarian cycles in females of the blowfly *Phormia regina*⁶. Topical application of altosid, a JH-mimic, increases the sensitivity of labellar chemoreceptors to stimulation with salt. It is interesting to note that, in several insect species, JH also influences feeding behavior and stimulates food intake, e.g. in lepidopterous larvae^{26,46,64} and females of *Culex* spp.⁴³. However, Meola⁴² reports that allatectomy in pharate females of *Aedes aegypti* does not prevent the development of biting behavior. Davis¹⁹ also reports that in *Aedes aegypti* a hemolymph-borne factor is responsible for a reduction of sensitivity in lactic acid receptors and correlates this with changes in host-seeking behavior following a blood meal. In the female spruce budworm moth, pheromone receptors show an increased sensitivity with aging, as demonstrated by EAG recordings. It is suggested that this may be due to the gradual disappearance of JH from the hemolymph of aging females, since topical application of altosid suppresses EAG responses⁴⁹.

In conclusion, receptor sensitivity seems in some cases to be under endocrine control. Hormones could act directly on the receptors, or indirectly by regulation of dendritic

liquor composition or sensillum pore size. A combination of these mechanisms cannot be excluded.

Peripheral regulating mechanisms

Apart from a centrally regulated mechanism (hormone, hemolymph composition, centrifugal control), a change in receptor responsiveness may be induced by a peripheral factor. When the different receptors in a sensillum show different degrees of change, or when a specific receptor only changes in response to a specific stimulus, this may seem difficult to reconcile with the idea of regulation by a common central factor. However, it is quite conceivable that different receptor cells react to the same factor, e.g. a hormone, with reactions differing in degree or even sign. This is what seems to happen in mosquito olfactory receptors in which the lactic acid-responsive cells decrease in sensitivity whereas the methyl butyrate-responsive cells show an opposite reaction²¹. When only a single receptor type is changed, e.g. a taste cell in a lepidopterous larva, which is continuously contacting its specific stimulus, it is difficult to understand how a general mechanism like a hormone, or the ionic environment of the receptors could cause this. Efferent nerve fibers, on the other hand, could of course very well exert a specific control.

Irrespective of the controlling agent, the receptor cell itself is (probably actively) involved in the setting of its sensitivity level. Conceivably two mechanisms could cause a change in its responsiveness: the number of receptor sites in its dendritic membrane could change, or the threshold of the spike generating mechanism could be affected. It has been suggested that in the case of lepidopterous larvae there is no change in receptor site number⁵⁹. When a receptor, due to exposure (via the diet) to salicin, reduces its sensitivity to salicin, it shows at the same time a reduced sensitivity to caffeine, in spite of the fact that this compound probably acts on different receptor sites on the same cell. This leads to the conclusion that either all receptor site types present change in number, or the change takes place at another, higher level or organization, such as the site of spike initiation where threshold changes may occur. Another possibility is a general change in dendritic properties. Moreover, the reduced sensitivity of the salicin receptor is (partly) carried over during a larval molt to the next instar. It is known that the dendritic ends of chemoreceptors are removed when the old cuticle is shed, and a new dendritic end is formed during each molt^{11,74}. These two observations led to the hypothesis that the spike generating process is changed, possibly by altering the resting potential of the cell, and the characteristics of the receptor sites (e.g. their number) remain constant⁵⁹.

To draw firm conclusions about which process a change of receptor sensitivity is based on, complete concentration-response curves at different sensitivity levels are required. Chemoreceptor function can quantitatively be described by three parameters: (1) stimulus concentration which elicits maximum response, (2) stimulus concentration which elicits 50% of maximal response (K_m), and (3) Hill-quotient, which is the slope of the concentration-response curve at 50% of maximal response point³¹. These parameters should be known when hypothesizing

on the physicochemical mechanism which underlies changes in receptor responsiveness. Such data are not yet generally available.

Sensory input and behavior

Although one would not expect a simple correlate of behavior with peripheral sensory input, behavior must, to some extent, be governed by that input. In the context of this review, an important issue is whether the receptor changes under discussion are of sufficient importance to lead to discernable changes in behavior. Several factors militate against the establishment of a firm and generalized answer to this question. Conditions which bring forth receptor changes may at the same time cause physiological changes, activate certain behavioral programs, or modify behavior due to learning processes. Therefore, correlations between receptor changes and behavioral changes do not necessarily indicate direct relationships. At the present time the relationship between the normal (unchanged) sensory message and behavior is only known for a few insects and in rather general terms, and, of course, several factors other than input from the external chemoreceptors also contribute to the initiation and maintenance of overt activity.

A number of studies relate the performance of taste receptors in response to key chemicals derived from host and non-host plants to the food selection behavior of the insects in an ecological context, and some²² have included studies on plant saps. In some work, aspects of the sensory message have been correlated with aspects of the performance of the insects in behavior tests. This has been done with locusts^{10,14}, flies^{23,27} and lepidopterous larvae^{12,15,41}. When the same individuals are used in both the behavioral and electrophysiological tests, very close correlation indeed may be obtained (Blanney and Simmonds, unpublished data on larvae of *Spodoptera* spp. and *Heliothis* spp.). It follows that there is at least the possibility that relatively small changes in receptor sensitivity may affect behavior performance significantly. Omand⁴⁷ postulates that, in blowflies, taste receptor modulation plays a dominant role in feeding regulation, although the reverse view is taken by Rachman⁵². Davis¹⁹ again holds the opinion that peripheral changes are of major importance and suggests that 'the peripheral sensory system exerts a significant, possibly determining, influence over the expression of certain behavior by female mosquitos'. Indeed, a strict correlation was found during the first few days after adult emergence between the beginning of host-seeking behavior and the presence of functioning lactic acid receptors in female mosquitos²⁰.

Different foods evoke modifications in the sensitivity of different taste receptors of tobacco hornworms. Changes in food preferences occur concomitantly, the insect showing a predilection for the plant on which it was grown⁶⁸. In the lateral styloconic sensillum of the maxilla a receptor cell, the 'deterrent' receptor, is stimulated by a range of compounds which deter feeding and which occur in non-favored plants. One such compound is salicin. Incorporating salicin in the diet of the larvae for several days results in a reduced firing rate in the deterrent receptor. A concomitant effect is that such larvae accept non-host plants which were previously rejected⁵⁷. It is important to

note that the time course of the sensory change and that of the behavioral change are similar.

Significance

Because the phenomenon of receptor modulation is still largely terra incognita, a discussion of its biological significance is necessarily of a speculative nature.

When receptor cells vary their sensitivity with certain physiological stages or life phases or former experiences, this will mean that the decision making is no longer restricted to the CNS only, but that the periphery is to a certain extent involved in this process as well. As shown by Davis' work, the CNS of a fed mosquito is not troubled by incoming information on host odors, in which it is not 'interested' at that moment¹⁹. The advantage of this 'decentralization' phenomenon may be found in the fact that this allows for a more efficient use of the nervous system as a whole. When the filtering of external stimuli by the receptors is not done in a constant or neutral mode, but rather according to the insect's needs, this will reduce the task of the CNS.

If, in the course of its development, a caterpillar becomes physiologically adapted to a certain host plant species, it may change its sensitivity to factors associated with the host plant. This could be achieved by altered receptor profiles, or by the CNS becoming 'tuned' to certain factors which are characteristic of the host plant. Change at the peripheral level would have the advantages outlined above. A further advantage of having receptors with a capacity to alter their sensitivity would be that of extending their dynamic range, which, of course, would give them greater overall capability⁴⁸.

If plasticity of the sensory system were a part of the food selection strategy of phytophagous insects, one might expect to find differences between oligophagous and polyphagous species. The former are more restricted in their range of plants and more protected from potential toxins in new plants by a behaviorally limiting sensory system; the latter, more generalist feeders, might profit from an ability to adapt quickly to new plants, or to learn by experience to avoid others²⁸. Indeed, Dethier, Yost²⁵ and Dethier²⁴ found a greater capacity to undergo aversion learning in polyphagous species, and Simmonds and Blaney⁶⁵ showed that polyphagous species surpass oligophagous species in their ability to undergo induction of food preference, not only at behavioral but also at peripheral sensory levels.

Concluding remarks

It is generally assumed that only neurones of the CNS can be modulated, for example in response to the presence of hormones^{36,37} or due to use or disuse^{5,40}. The reports cited in this review, though limited in number, seem to negate this notion and indicate that peripheral chemoreceptors may possess a certain plasticity. It is as yet impossible to conjecture about the generality of this phenomenon. The fact that it has been observed in different insect orders and in different ontogenetic phases could support the hypothesis that this property is widespread among insects. Future research should discover whether this is true and whether its occurrence is limited to insects or extends

to other organisms. At present it can be stated that the phenomenon of sensory modulation opens an interesting new vista on the role of receptors in the control of insect behavior.

- 1 Acknowledgments. We thank R. F. Chapman and F. E. Hanson for criticism.
- 2 To whom reprint requests should be addressed.
- 3 Permanent address: Department of Entomology, Agricultural University, Wageningen, The Netherlands.
- 4 Present address: Jodrell Laboratory, Royal Botanic Gardens, Kew, Richmond, Surrey TW9 3 DS, England.
- 5 Alkon, D. L., Calcium-mediated reduction of ionic currents: a biophysical memory trace. *Science* 226 (1984) 1037–1045.
- 6 Angioy, A. M., Liscia, A., Crnjar, R., and Pietra, P., An endocrine control mechanism for chemosensillar activity in the blowfly. *Experientia* 39 (1983) 545–546.
- 7 Angioy, A. M., Liscia, A., and Pietra, P., Cyclic sensitivity variations in the labellar chemosensilla of *Calliphora*. *Experientia* 39 (1983) 546–547.
- 8 Bernays, E. A., and Chapman, R. F., The control of changes in the peripheral sensilla associated with feeding in *Locusta migratoria* (L.). *J. exp. Biol.* 57 (1972) 755–763.
- 9 Bernays, E. A., Blaney, W. M., and Chapman, R. F., Changes in chemoreceptor sensilla on the maxillary palps of *Locusta migratoria* in relation to feeding. *J. exp. Biol.* 57 (1972) 745–753.
- 10 Blaney, W. M., Chemoreception and food selection in locusts. *TINS* (1981) 35–38.
- 11 Blaney, W. M., Chapman, R. F., and Cook, A. G., The structure of the terminal sensilla on the maxillary palps of *Locusta migratoria* (L.), and changes associated with moulting. *Z. Zellforsch.* 121 (1971) 48–68.
- 12 Blaney, W. M., and Simmonds, M. S. J., Electrophysiological activity in insects in response to antifeedants. *TDR Misc. Pub. Lond.* (1983) 219.
- 13 Blaney, W. M., and Simmonds, M. S. J., Experience of chemicals alters the taste sensitivity of lepidopterous larvae. *Chem. Senses* 8 (1984) 245.
- 14 Blaney, W. M., and Winstanley, C., Chemosensory mechanisms of locusts in relation to feeding: the role of some secondary plant compounds. In: *Insect Neurobiology and Pesticide Action*. *Neurotoxicology* 79 (1980) 383–389.
- 15 Blom, F., Sensory activity and food intake: a study of input-output relationships in two phytophagous insects. *Neth. J. Zool.* 28 (1978) 277–340.
- 16 Broyles, J. L., Hanson, F. E., and Shapiro, A. M., Ion dependence of the tarsal sugar receptor of the blowfly *Phormia regina*. *J. Insect Physiol.* 22 (1976) 1587–1600.
- 17 Clark, J. V., Changes in the feeding rate and receptor sensitivity over the last instar of the African armyworm, *Spodoptera exempta*. *Ent. exp. appl.* 27 (1980) 144–148.
- 18 Cook, A. G., The ultrastructure of the A1 sensilla on the posterior surface of the clypeo-labrum of *Locusta migratoria migratorioides* (R. & F.). *Z. Zellforsch.* 134 (1972) 539–554.
- 19 Davis, E. E., Regulation of sensitivity in the peripheral chemoreceptor systems for host-seeking behaviour by a hemolymph-borne factor in *Aedes aegypti*. *J. Insect Physiol.* 30 (1984) 179–183.
- 20 Davis, E. E., Development of lactic acid-receptor sensitivity and host-seeking behavior in newly emerged female *Aedes aegypti* mosquitoes. *J. Insect Physiol.* 30 (1984) 211–215.
- 21 Davis, E. E., and Takahashi, F. T., Humoral alteration of chemoreceptor sensitivity in the mosquito. *Olfaction and Taste* 7 (1980) 139–142.
- 22 Dethier, V. G., Electrophysiological studies of gustation in lepidopterous larvae. II. Taste spectra in relation to food-plant discrimination. *J. comp. Physiol.* 82 (1973) 103–134.
- 23 Dethier, V. G., *The hungry fly*. Harvard University Press, Cambridge 1976.
- 24 Dethier, V. G., Food-aversion learning in two polyphagous caterpillars, *Diacrisia virginica* and *Estigmene congrua*. *Physiol. Ent.* 5 (1980) 321–325.

- 25 Dethier, V. G., and Yost, M. T., Oligophagy and absence of food-aversion learning in tobacco hornworms, *Manduca sexta*. *Physiol. Ent.* 4 (1979) 125–130.
- 26 Dominick, O. S., and Truman, J. W., The physiology of wandering behavior in *Manduca sexta*. I. Temporal organization and the influence of the internal and external environments. *J. exp. Biol.* 110 (1984) 35–41.
- 27 Getting, P. A., The sensory control of motor output in fly proboscis extension. *Z. vergl. Physiol.* 74 (1971) 103–120.
- 28 Gelperin, A., and Forsythe, D., Neuroethological studies of learning in mollusks, in: *Simpler Networks and Behaviour*, pp. 239–250. Ed. J. C. Fentress. Sinauer Associates, Sunderland 1975.
- 29 Hall, M. J. R., Central control of tarsal threshold for proboscis extension in the blowfly. *Physiol. Ent.* 5 (1980) 17–24.
- 30 Hall, M. J. R., Circadian rhythms of proboscis extension responsiveness in the blowfly; central control of threshold changes. *Physiol. Ent.* 5 (1980) 223–233.
- 31 Hansen, K., Insect chemoreception. *Receptors and Recognition (B)* 5 (1978) 233–292.
- 32 Hellekant, G., Influences on the impulse pattern in efferent chorda tympani nerve fibers in the rat. *Olfaction and Taste* 4 (1972) 308–315.
- 33 Hodgson, E. S., Taste receptors of arthropods. *Symp. zool. Soc. London* 23 (1968) 269–277.
- 34 Horn, E., *Vergleichende Sinnesphysiologie*. Gustav-Fischer-Verlag, Stuttgart 1982.
- 35 Jachmann, H., Zweyffening, R. C. V. J., and Van der Molen, J. N., Effects of hemolymph free cations on blowfly taste receptor responses. *J. Insect Physiol.* 28 (1982) 943–946.
- 36 Kandel, E. R., Krasne, F. B., Strumwasser, F., and Truman, J. W., Cellular mechanisms in the selection and modulation of behaviour. *Neurosci. Res. Program Bull.* 17 (1979) 523–710.
- 37 Kandel, E. R., and Schwartz, J. H., Molecular biology of learning: modulation of transmitter release. *Science* 218 (1982) 433–443.
- 38 Kramer, J. J. de, and Molen, L. G. Vander, Development of labellar taste hairs in the blowfly, *Calliphora vicina* (Insecta, Diptera). *Zoomorphology* 104 (1984) 1–10.
- 39 Küppers, J., and Thurm, U., Humoreale Steuerung eines Ionentransports an epithelialen Rezeptoren von Insekten. *Verh. dt. zool. Ges.* 67 (1975) 46–50.
- 39a Küppers, J., and Thurm, U., On the functional significance of ion circulation induced by electrogenic transport, in: *Exogenous and Endogenous Influences on Metabolic and Neural Control*, vol. 1, pp. 313–327. Eds A. D. F. Addink and N. Spronk. Pergamon Press, Oxford 1982.
- 40 Lynch, G., and Baudry, M., The biochemistry of memory: a new and specific hypothesis. *Science* 224 (1984) 1057–1063.
- 41 Ma, W. C., Dynamics of feeding responses in *Pieris brassicae* Linn. as a function of chemosensory input: a behavioral, ultrastructural and electrophysiological study. *Mededelingen Landbouwhogeschool Wageningen* 72 (1972) 1–162.
- 42 Meola, R. W., cited in Davis¹⁹.
- 43 Meola, R. W., and Petralia, R. W., Juvenile hormone induction of biting behaviour in *Culex* mosquitoes. *Science* 209 (1980) 1548–1550.
- 44 Meijsser, F. M., Internal report, Department of Animal Physiology, Agricultural University, Wageningen 1983.
- 45 Moulins, M., and Noirot, C., Morphological features bearing on transduction and peripheral integration in insect gustatory organs. *Olfaction and Taste* 4 (1972) 49–55.
- 46 Muraleedharan, D., and Prabha, V., Hormonal influence on feeding and digestion in a plant bug, *Dysdercus cingulatus* and a caterpillar *Hyblaea puera*. *Physiol. Ent.* 6 (1981) 183–189.
- 47 Omand, E., A peripheral sensory basis for behavioural regulation. *Comp. Biochem. Physiol. (A)* 38 (1971) 265–278.
- 48 Omand, E., and Zabara, J., Response reduction in dipteran chemoreceptors after sustained feeding or darkness. *Comp. Biochem. Physiol. (A)* 70 (1981) 469–478.
- 49 Palaniswamy, P., Seabrook, W. D., and Sivasubramanian, P., Effect of a juvenile hormone analogue on olfactory sensitivity of eastern spruce budworm, *Choristoneura fumiferana* (Lepidoptera: Tortricidae). *Ent. exp. appl.* 26 (1979) 175–179.
- 50 Palaniswamy, P., Sivasubramanian, P., and Seabrook, W. D., Modulation of sex pheromone perception in female moths of the eastern spruce budworm, *Choristoneura fumiferana* by altosid. *J. Insect Physiol.* 25 (1979) 571–574.
- 51 Phillips, C. E., and Vande Berg, J. S., Directional flow of sensillum liquor in blowfly (*Phormia regina*) labellar chemoreceptors. *J. Insect Physiol.* 22 (1976) 425–429.
- 52 Rachman, N., The sensitivity of the labellar sugar receptors of *Phormia regina* in relation to feeding. *J. Insect Physiol.* 25 (1979) 733–739.
- 53 Rees, C. J. C., Age dependency of response in an insect chemoreceptor sensillum. *Nature* 227 (1970) 740–742.
- 54 Roelofs, W. L., and Comeau, A., Sex pheromone perception: electroantennogram responses of the red-banded leaf roller moth. *J. Insect Physiol.* 17 (1971) 1969–1982.
- 55 Ross, R. J., Palaniswamy, P., and Seabrook, W. D., Electroantennograms from male and female spruce budworm (*Choristoneura fumiferana* (Chem.)) for different ages and pheromone concentrations. *Can. Ent.* 111 (1979) 807–816.
- 56 Schoonhoven, L. M., Loss of hostplant specificity by *Manduca sexta* after rearing on an artificial diet. *Ent. exp. appl.* 10 (1967) 270–272.
- 57 Schoonhoven, L. M., Sensitivity changes in some insect chemoreceptors and their effect on food selection behavior. *Proc. koninkl. ned. Akad. Wetensch. (C)* 72 (1969) 491–498.
- 58 Schoonhoven, L. M., On the variability of chemosensory information. *Symp. Biol. Hung.* 16 (1976) 261–266.
- 59 Schoonhoven, L. M., Long-term sensitivity changes in some insect taste receptors. *Drug Res.* 28 (1978).
- 60 Schoonhoven, L. M., What makes a caterpillar eat? The sensory code underlying feeding behavior, in press 1985.
- 61 Schoonhoven, L. M., Unpublished results.
- 62 Schweitzer, E. S., Sanes, J. R., and Hildebrand, J. G., Ontogeny of electroantennogram responses in the moth, *Manduca sexta*. *J. Insect Physiol.* 22 (1976) 955–960.
- 63 Seabrook, W. D., Hirai, K., Shorey, H. H., and Gaston, L. K., Maturation and senescence of an insect chemosensory response. *J. chem. Ecol.* 5 (1979) 587–594.
- 64 Sieber, R., and Benz, G., The influence of juvenile hormone on the feeding behavior of last-instar larvae of the codling moth, *Laspeyresia pomonella* (Lep., Tortricidae). *Experientia* 34 (1978) 1647–1650.
- 65 Simmonds, M. S. J., and Blaney, W. M., Some effects of azadirachtin on lepidopterous larvae. *Proc. 2nd. Int. Neem. Conf.* Eds H. Schmutterer and K. R. S. Ascher. GTZ, Eschborn (1984) 163–180.
- 66 Simpson, S. J., An oscillation underlying feeding and a number of other behaviors in fifth-instar *Locusta migratoria* nymphs. *Physiol. Ent.* 6 (1981) 315–324.
- 67 Spencer, M., and Case, J. F., Exogenous ecdysteroids elicit low-threshold sensory responses in spiny lobsters. *J. exp. Zool.* 229 (1984) 163–166.
- 68 Städler, E., and Hanson, F. E., Influence of induction of host preference on chemoreception of *Manduca sexta*: behavioral and electrophysiological studies. *Symp. Biol. Hung.* 16 (1976) 267–273.
- 69 Stoffolano, J. G., Effect of age and diapause on the mean impulse frequency and failure to generate impulses in labellar chemoreceptor sensilla of *Phormia regina*. *J. Geront.* 28 (1973) 35–39.
- 70 Stoffolano, J. G., Control of feeding and drinking in diapausing insects, in: *Experimental analysis of insect behavior*, pp. 32–47. Ed. L. Barton Browne. Springer, New York 1974.
- 71 Stoffolano, J. G., Damon, R. A., and Desch, C. E., The effect of age, sex and anatomical position on peripheral responses of taste receptors in blowflies, genus *Phormia* and *Protophormia*. *Exp. Geront.* 13 (1978) 115–124.
- 72 Stürckow, B., Holbert, P. E., and Adams, J. R., Fine structure of the tip of chemosensitive hairs in two blowflies and the stable fly. *Experientia* 23 (1967) 780–782.
- 73 Stürckow, B., Holbert, P. E., Adams, J. R., and Anstead, R. J., Fine structure of the tip of the labellar taste hair of the blowflies, *Phormia regina* (Mg.) and *Calliphora vicina* R.-D. (Diptera: Calliphoridae). *Z. Morph. Tiere* 75 (1973) 87–109.
- 74 Wensler, R. J., and Filshie, B. K., Gustatory sense organs in the food canal of aphids. *J. Morph.* 129 (1969) 473–492.
- 75 Wolk, F. M. Van der, Koerten, H. K., and Starre, H. Van der, The external morphology of contact chemoreceptive hairs of flies and the motility of the tips of these hairs. *J. Morph.* 180 (1984) 37–54.
- 76 Zacharuk, R. Y., Ultrastructure and function of insect chemosensilla. *A. Rev. Ent.* 25 (1980) 27–47.