REVIEW

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"Allohormones": a class of bioactive substances favoured by sexual selection

Abstract During close bodily contact, many species transfer substances that influence the behaviour or physiology of conspecifics. Such transfer is especially common during courtship and copulation. When this is the case the involved bioactive substances are favoured by sexual selection because their effects include increased egg production, inhibited remating, and changed sperm transport or storage in the partner. The direct mode of action of these substances is fundamentally different from that of pheromones and nuptial gifts. Therefore, the term allohormone is introduced here. An allohormone is defined as a substance that is transferred from one individual to another free-living member of the same species and that induces a direct behavioural or physiological response, bypassing external sensory organs. Although we emphasise the importance of allohormones in reproductive processes, allohormones may also have important functions outside of copulation.

Keywords Allohormone · Hormone · Pheromone · Nuptial gift · Sexual selection

Introduction

Close bodily contact enables animals to transfer substances that influence the behaviour or physiology of the

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partner. In many species this transfer occurs during courtship and copulation. Usually such substances are male products, and their mode of action is fundamentally different from pheromones and nuptial gifts. Because the transfer is often a covert process, many of these chemical "gifts" have been discovered only recently. Their biological effects – including increased egg laying, inhibition of remating and effects on sperm transport or storage – are important in terms of sexual selection (Eberhard and Cordero 1995). Nonetheless, no single defining term exists; instead, the agents involved have been assigned diverse and descriptive names like allocrine, seminal factor, sex peptide, ejaculate substance, male sexual product, and (male) accessory gland secretion. Although all these names correctly describe functions and sources, there is the need for a unifying term for this important class of biologically active substances. We propose to use the term allohormone, which has already been used to describe the substance carried on the love dart of the garden snail *Helix aspersa* (Koene and Chase 1998).

The definition of allohormones

We define allohormones as substances that are transferred from one individual to another free-living member of the same species and that induce a direct physiological response, bypassing sensory organs. In this paper, we will focus on allohormones that are transferred during mating, although such substances are not limited to reproductive processes. For example, growth factors that are involved in parent-offspring care (e.g. Schutz and Barlow 1997) and hormonal components of milk secreted during lactation (e.g. Buts 1998) also fall within our definition. However, note that our definition does not include nuptial gifts because these give either direct energetic or defensive benefits to the mating partner or the offspring (e.g. Eisner et al. 1996; Smedley and Eisner 1996) and do not manipulate the receiver's physiology.

Karlson and Lüscher (1959) proposed the term "telemone" for a class of, then still hypothetical, biologically active substances similar to the ones we are concerned with here. At the time such substances had not yet been identified, but the imaginary substances were believed to diffuse into the blood from the digestive system. Since then, it has become clear that many of these substances are transferred during close bodily contact, which makes the term telemone (Gk. *tele*, at a distance; *horman*, to excite, to arouse), meaning "arousal at a distance", counterintuitive and inadequate. Allohormone (Gk. *allos*, other), meaning "arousal by another", is a more appropriate term.

Allohormones are not to be confused with the etymologically close allomones, a term used for interspecific pheromones. Allomones are secreted by one individual causing an individual of another species to react favourably. An example is the defence secretion of ticks against predator ants (Yoder et al. 1993). Substances released by parasites to influence their hosts (e.g. De Jong-Brink et al. 1999) can also be seen as allomones. Although the two terms have an etymological resemblance, the functions of allomones and allohormones are very distinct.

Allohormones are different from hormones and pheromones

Unlike endocrine hormones, allohormones are transferred between individuals. Endocrine hormones are produced by specialised tissues, and transported within individuals, via the blood, to other tissues where they induce specific physiological responses. Like hormones, allohormones induce physiological responses in specific organs. On the molecular level, allohormones can be identical to or derived from hormones produced and used in the reproductive system of the receiving animal. For example, hormones, such as prostaglandins, are added to semen by male accessory glands (e.g. Loher et al. 1981; Mann and Lutwik-Mann 1981). In humans, prostaglandins induce contractions of the smooth muscles of the uterus; thus, they potentially promote sperm transport (reviewed by Eberhard 1996). However, regardless of their exact molecular structure and chemical properties, as long as they behave like hormones, any peptide, protein or other large molecule can function as an allohormone.

Allohormones are also fundamentally different from pheromones (Gk. *pherein*, to transfer). Pheromones have been defined as substances that are released to the outside of one animal, often in minute amounts, and are detected by specialised sensory structures in another member of the species where they induce a specific reaction (Karlson and Lüscher 1959). For example, in many species of moths the males' specialised antennae, which are extremely sensitive to the volatile pheromonal signals of females, allow males to locate females from as far as one hundred meters (Bradbury and Vehrencamp

1998). Like pheromones, allohormones are secreted outside the body by specialised glands; but unlike pheromones, allohormones enter the body of a conspecific to act directly on target organs, bypassing external sensory structures.

It follows from the definition of the allohormone class that some of the substances labelled as pheromones that are transferred during physical contact should be included in this new class. For example, some plethodontid (lungless) salamanders, e.g. the dusky salamander *Desmognathus fuscus* (Arnold and Houck 1982), transfer a secretion that increases female receptivity, which results in a higher probability that the female will accept the male's spermatophore (Houck and Reagan 1990; Houck 1998). This secretion is produced by the mental gland. During courtship the male bites or hits the skin of the female with specialised pre-maxillary teeth that are associated with this mental gland. The secretion from the gland is introduced through the skin injury directly into the blood of the female and presumably the allohormone in this secretion acts directly on the brain.

Other contact pheromones act on specialised chemosensory receptors and should remain classified as "classical" pheromones (Karlson and Lüscher 1959). Examples of this are found in many reptiles and mammals, in which pheromones are detected by the vomeronasal organ (Døving and Trotier 1998). For instance, in garter snakes, *Thamnophis sirtalis parietalis*, tongue flicking behaviour of the male serves to deliver a female skin secretion to the vomeronasal organ. The pheromone molecules in the skin secretion are detected by the organ's specialised chemoreceptors and evoke courtship behaviour via these receptors (Mason et al. 1989).

Allohormone examples from sexual selection

There are many reviews that deal with male substances that influence female reproduction (e.g. Eberhard and Cordero 1995; Eberhard 1996), especially in insects (e.g. Gillott 1988). Here, we focus on a few examples to illustrate some of the principles of allohormones. Allohormones can act either directly on the central nervous system or on the peripheral organs of the recipient. Centrally acting allohormones can induce oviposition, as was first shown in the fruit fly *Drosophila funebris* (Baumann 1974a, 1974b). Likewise, they can inhibit remating of the female by acting on the central nervous system, as was demonstrated in the house fly *Musca domestica* (Riemann et al. 1967; Leopold et al. 1971a, 1971b). Allohormones can also have peripheral effects that result in oviposition or inhibition of remating. This has been reported in the barnacle *Balanus balanoides* (Barnes et al. 1977) and the adder *Vipera berus* (Andrén and Nilson 1987), respectively. Similarly, peripherally acting allohormones have been found to induce sperm transport in the assassin bug *Rodnius prolixus* (Davey 1958), and sperm storage in *Drosophila melanogaster* (Harsmann and Prout 1994). In all these examples the

allohormones are transferred during copulation together with the sperm. However, it was recently reported that in the nematode *Caenorhabditis elegans* the sperm itself produces an allohormone that influences the physiology of the female (Miller et al. 2001). Additionally, allohormone transfer can also take place before sperm is donated, i.e. during courtship. This mode of transfer is found in the previously mentioned examples of the salamander *Desmognathus fuscus* (Arnold and Houck 1982) and the garden snail *Helix aspersa* (Koene and Chase 1998). Two further examples could be the copulatory setae of the common earthworm *Lumbricus terrestris* (Grove 1925; J.M. Koene et al., unpublished observations) and the sexual sting of some scorpion species, e.g. the giant hairy desert scorpion *Hadrurus arizonensis* (Tallarovic et al. 2000).

All of the abovementioned allohormones increase the donor's reproductive success, and therefore play a role in sexual selection. Because they benefit the donor's reproduction, by increasing the chance that the donated sperm will fertilise the partner's eggs, allohormones can evolve through intrasexual selection (reviewed in Birkhead and Møller 1998). Such mechanisms can evolve as "sensory traps" in which the male function takes advantage of female traits evolved under natural selection (West-Eberhard 1979; Eberhard 1998). An allohormone can act upon such a pre-existing sensitivity if it is similar or identical to a substance already used in the female reproductive endocrinology. At least theoretically, it is also possible that a toxic allohormone evolves as a harmful tactic only to impose a cost of mating on the partner, thereby making remating of that partner less likely and thus reducing the risk of sperm competition (Johnstone and Keller 2000).

However, (cryptic) mate choice can equally well cause the evolution of allohormones (Cordero 1998). In a Fisherian runaway process (Fischer 1930) the mate preference based on an arbitrary substance can become exaggerated due to the positive co-evolutionary feedback between the signaller and the receiver. For the "good genes" hypothesis (Andersson 1994) or handicap principle (Zahavi and Zahavi 1997) an allohormone can function as a signal of quality to the partner. Finally, a chase-away selection process (Holland and Rice 1998) leads to antagonistic co-evolution that can cause exaggeration of the trait (in this case the allohormone) due to the intersexual conflict.

In order to determine whether a trait has evolved due to intrasexual or intersexual selection, experiments have to be carefully designed to tease apart the alternative hypotheses. Such experiments have recently been performed on dart shooting in *H. aspersa*, in which the observed dart shooting behaviour was found to conform to the behaviour predicted by the intrasexual selection hypothesis of mate manipulation (J.M. Koene and R. Chase, unpublished observations). Similarly, in *D. melanogaster* it was shown that an allohormone transferred by the male increased his reproductive success, but at the same time was toxic for the female. This situation causes a conflict of interest (between the sexes) resulting in a continuous arms-race between mate manipulation of the partner and avoidance of this manipulation (Chapman and Partridge 1996; Rice 1996; Stockley 1997).

In recent sexual selection research many substances that play a role in mate manipulation or mate choice have been discovered, and these can be expected to be found in most internally fertilising species. We believe that the term allohormone will prove to be useful to refer to bioactive substances that are transferred between individuals of the same species and that affect the receiver's physiology.

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