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REVIEW ARTICLE

Synaptic plasticity in cephalopods; more than just learning and memory?

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Abstract The outstanding behavioural capacity of cephalopods is underpinned by a highly sophisticated nervous system anatomy and neural mechanisms that often differ significantly from similarly complex systems in vertebrates and insects. Cephalopods exhibit considerable behavioural flexibility and adaptability, and it might be expected that this should be supported by evident cellular and synaptic plasticity. Here, we review what little is known of the cellular mechanisms that underlie plasticity in cephalopods, particularly from the point of view of synaptic function. We conclude that cephalopods utilise short-, medium-, and long-term plasticity mechanisms that are superficially similar to those so far described in vertebrate and insect synapses. These mechanisms, however, often differ significantly from those in other animals at the biophysical level and are deployed not just in the central nervous system, but also to a limited extent in the peripheral nervous system and neuromuscular junctions.

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Introduction

Plasticity may be broadly defined as the latent capacity that an organism, or system has to alter its properties in response to a significant external stimulus. As far as neural or synaptic plasticity are concerned, it has been assumed that this was a property of 'advanced' brains, and as a result, most attention has been paid to vertebrate (mammalian) systems. However, in the last 10 years, information has emerged from the study of cephalopod nervous systems, which with work on other invertebrates, suggests that plasticity may be a key and distinctive property of biological neural networks.

Cephalopods are notable for their relatively large CNS and outstanding behavioural capabilities (Hanlon and Messenger 1998). The anatomy and connectivity of the nervous systems of many species have been compared anatomically (Nixon and Young 2003), and this, along with data from a large body of behavioural experiments (see Hanlon and Messenger 1998), has allowed some modelling of the potential pathways for learning and motor control to be elaborated (Young 1991). It would seem axiomatic that such behavioural flexibility should be underpinned by suitable cellular and synaptic flexibility or 'plasticity.' However, only in the last 10 years or so have any details about the mechanisms that might underlie plasticity emerged. This may seem surprising when one considers that the peripheral nervous systems of decapod cephalopods have provided several useful model synaptic systems, among these, the giant axon (Williams 1910; Young 1935),

the giant synapse of the stellate ganglion (Bullock 1948), and neuromuscular junctions including the those within the unique, centrally controlled chromatophore system in the skin (Sereni and Young 1932). Such preparations have subsequently been used to make fundamental contributions to basic neuroscience (e.g., Hodgkin and Huxley 1952; Bloedel et al. 1966; Katz and Miledi 1966; Florey et al. 1985). Yet, despite the availability of these peripheral nervous system preparations, there have been few efforts to evaluate conclusively if such synapses exhibit any dynamic properties.

Given what we know about the 'central' nervous system of cephalopods, as well as their great utility as material for neurobiological preparations, it is surprising that these animals have only recently been exploited by cellular and systems neurobiologists. (Williamson et al. 1993; Budelmann et al. 1995). Part of the difficulty is due to the fact that 'CNS' cells in cephalopods, though numerous and organised into identifiable functional lobes with defined layers of cells, have relatively small cell bodies. When Young measured nuclear diameter across the lobes of octopus, he found they averaged 5–20 μm diameter, reflecting the small diameter of the majority of cells (see e.g. Young 1963, 1971). This size renders electrophysiological recording from single cells difficult. An additional complication is that, like most invertebrates, central synaptic signalling occurs in a neuropil that is usually several length constants removed from the recording site, and transmitted electrical signals do not necessarily pass via the cell body as they do in vertebrate neurones (See Fig. 1). As most intracellular recordings are made from cell bodies, the recording and interpretation of signals in such a CNS are extremely problematic. In this short review, we summarise what is known about synaptic plasticity in cephalopods, try to integrate information from both peripheral and central nervous systems, and indicate possible directions for future research.

Synaptic plasticity

Although in this review, we are dealing with synaptic plasticity, the reader should be aware that plasticity is an extremely diffuse concept that one may find applied in fields as widely separated as evolutionary theory (Baldwin 1896; Waddington 1942, see Crispo 2007) behavioural (Konorski 1948; Hebb 1949 reprinted in Hebb 2002) and cellular neuroscience. It may be defined as the inherent potential of a network or system to alter appropriately and permanently, or semi-permanently, in response to a significant stimulus, such that its output properties are changed, or as Hebb succinctly stated in relation to neurones:

> When an axon of cell A is near enough to excite cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased. (Hebb 1949 reprinted in Hebb 2002)

Equally, one might add, the efficiency could also be significantly decreased by the external stimulus or, in the case of the 'stimulus' of nerve damage, effectively recover the *status quo*. Such a concept of systemic plasticity (flexibility) extends from the molecular level through genomes, phenotypes, ecosystems, and generally, all selective developmental and evolutionary processes (Crispo 2007).

The idea that alterations in synaptic function may underlie plastic behaviours such as learning and memory arose relatively early in the history of neuroscience: Konorski was the first to apply the term 'plasticity' (Konorski 1948) and almost simultaneously Donald Hebb proposed that use-dependent changes in synapses may underlie learning phenomena (1949 reprinted as Hebb 2002). But a cellular basis for these concepts was not forthcoming until Bliss and Lomo's groundbreaking experiments on slices

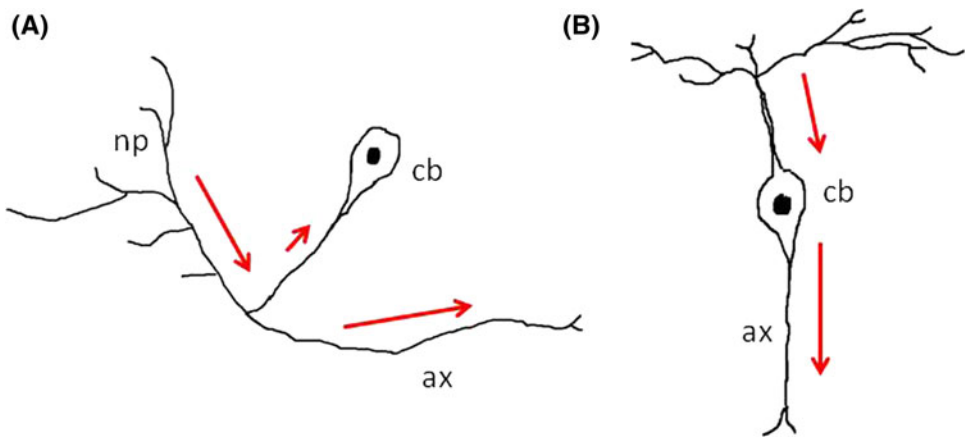

Fig. 1 Diagram of Cephalopod (**a**) and vertebrate-like CNS neurones (**b**) compared. *Red arrows* indicate the flow of electrical signals from synapse to axons (ax). In a typical cephalopod neurone, electrical signalling and chemical transmission occur in the neuropil (np) the cell body (cb) is 'by-passed' (colour figure online)

from rat hippocampus that demonstrated that in this learning and memory network, repeated stimulation of the perforant pathway evoked a long-term increase in synaptic strength (they termed this increase 'Long-Term Potentiation,' or LTP) (Bliss and Lomo 1973). Although this Hebbian type of synaptic plasticity would seem to go a long way towards explaining the synaptic basis for learning and memory and behavioural plasticity, it is by no means the only possible theoretical mechanism that could provide an increase in the 'strength' of transmission. Indeed, in molluscs, non-synaptic (axonal and dendritic) mechanisms are generated by stimulus-dependent changes in membrane conductance and have been implicated in both potentiation and learning and memory (Kemenes et al. 2006; Benjamin et al. 2008). However, with the notable exceptions of the squid giant synapse, Calyx of Held (a key giant central synapse in the mammalian auditory brainstem circuit that helps in the discrimination of the relative position of sounds), and the chick ciliary ganglion (a parasympathetic ganglion located in the posterior orbit of the eye) (see Martin et al. 1963; Stanley 1989; Yawo 1990), direct simultaneous recording from pre- and postsynaptic zones of synapses is exceptionally difficult in both mammalian and invertebrate preparations. Recordings are normally made from cell bodies at least several hundreds of microns and several length constants distant from the synaptic zones. Unfortunately, none of the key synaptic 'giant' preparations previously mentioned are noted for their prominent synaptic plasticity and none of them are located in learning and memory areas. Instead, indirect methods such as field potential recordings, which enable both pre- and postsynaptic signals for populations of neurones to be estimated, have been used. Or alternatively, the output properties of the stimulated system (postsynaptic recording only) have been employed. This is not an ideal situation, as in any signal analysis scenario, it is necessary to know both the input and output properties. Although such recording fails to get at the underlying mechanisms, it can provide information that may allow the evaluation of the potential of the tissue for plasticity.

How does one define or measure plasticity? There is an enormous literature in the field of synaptic plasticity, and yet there is no sure way to make comparisons between preparations and animals. A possible starting point is to define the kinds of phenomena that are observed; to this end, we can summarise what is seen at the level of synaptic input–output relationships in plastic and non-plastic synapses in the diagram presented in Fig. 2. In reviewing this, the reader will be better equipped to evaluate the types of synapses and their input–output relations that we will describe in the following sections. Figure 2 graphically represents most of the possible arrangements observed at synaptic junctions. In actual recordings, the inputs and responses may be as follows: applied currents, pre-synaptic recordings, postsynaptic potentials, field potentials, currents, calcium transients, or indeed any quantitative or semi-quantitative means of measuring synaptic input and outputs. Reading from right to left in the figure: The diagram on the far right shows two idealised neurones, where both pre- and postsynaptic responses are recorded. The two traces represent, respectively, from bottom to top, the pre-synaptic stimulus 'intensity' and the postsynaptic response intensity. In the first case (1), a single pre-synaptic stimulus produces a postsynaptic response (synaptic transmission (ST)). In the second case (2), a train of identical pre-synaptic stimuli produce initially an identical postsynaptic response and then a *facilitating* response to identical synaptic input. In the third scenario, an initially identical postsynaptic response is followed by a stimulus-dependent *depression* (3). Subsequent stimulation of the synapse after a period of rest may result in a situation where there is an immediate *short-term potentiation* (3–10 min- (4) or *depression* (5). Facilitation, depression, and short-term potentiation or short-term depression are behaviours seen in many synapses. The final two scenarios show, respectively, long-term potentiation and depression (6, 7). In the case of short- and long-term potentiation and depression, the input–output properties have been permanently altered. Indeed, such features are believed to comprise the cellular substrate that underpins learning and memory, particularly spatial learning in vertebrates (Morris et al. 1986). Notably, cephalopods, which evolved in competition with vertebrates, have many parallel, though not necessarily identical, physiological mechanisms (Packard 1972). Cephalopods have the experimental advantage over other invertebrates of presenting a brain with specialised lobes formed of layers of neurones which are interconnected by well-defined nerve tracts. Thus, it is possible to make brains slices and stimulate/record from the nerve tracts and lobes. This means that cephalopods present a brain model that may be considered to be an alternative, though comparable, system to vertebrate brains. Studying cephalopod brains may help to give an answer to the question of whether the mechanisms underlying plasticity are so basic that they are common to all animals or if there are alternative mechanisms to these we know of in vertebrates.

The 'CNS' central lobes

The central brain masses of decapod and octopod cephalopods present as a cluster of circumoesophageal lobes in dorsal view (Fig. 3). In addition to these lobes, two relatively massive optic lobes (OLs) lie on either side of the central 'brain,' one behind each eye. A large body of work is available on octopod brains [mainly *Octopus vulgaris*

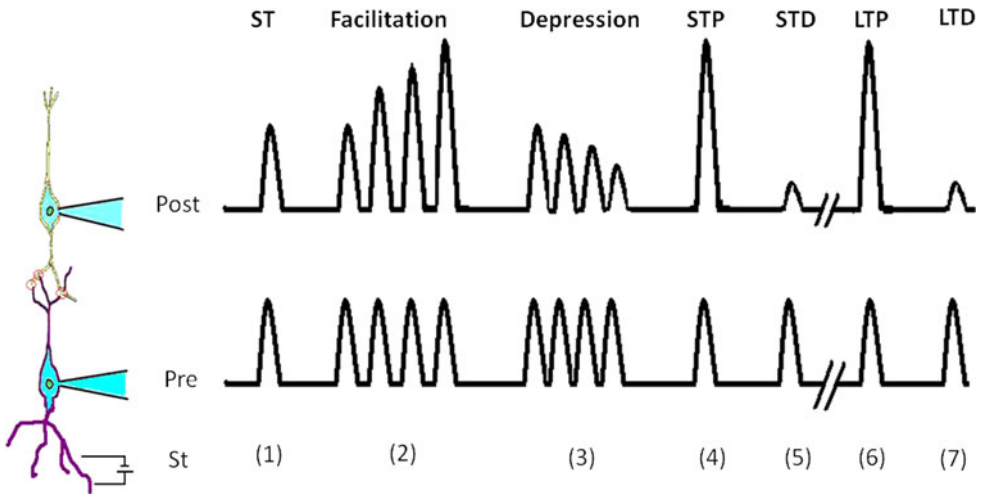

Fig. 2 Diagrammatic representation of some of the possible input–output relations seen in synaptic preparations from the point of view of synaptic plasticity based on mammalian data. The recording arrangement from two idealised vertebrate-like neurones is shown on *left-hand side* and relates directly to the recordings seen in the *lower* (pre) and *upper* (post) synaptic responses. In this ideal scenario pre-synaptic, stimuli are always of similar magnitude (generally these responses are not seen under most experimental conditions). The postsynaptic responses are seen to vary depending on the stimulation conditions. (*1*) ST, synaptic transmission shows the baseline pre-and postsynaptic responses, (*2*) a train of pre-synaptic stimuli produce a facilitation of the postsynaptic response, (*3*) a train of pre-synaptic stimuli produce a depression, (*4*) after a train of stimuli, a short-term potentiation of synaptic transmission is seen (this response later subsides, not shown), (*6*) and (*7*) show, respectively, long-term potentiation (LTP) and depression (LTD). In this review, we show that all of these types of synaptic plasticity have been seen in separate preparations of cephalopod synapses

(Wells 1978)]. On the basis of lesion experiments and connectivity maps, the suboesophageal lobes of octopus are thought to be primarily motor in function, and the supra-oesopagal lobes are thought to represent key integrative elements in the formidable learning and memory circuits of these animals. Of particular interest is the vertical lobe complex on the superior brain surface. Stimulating (Wells 1978) or recording from this area yields neural activity in the living animal that is apparently uncorrelated with motor function (Bullock and Basar 1988; Brown et al. 2006). The optic lobes seem to have a combined visual recognition, motor, and learning function. Interestingly, the cortical layers of the OL have a strict laminar structure that resembles the neuronal part of vertebrate retina (albeit without the photoreceptors which are located in the eye orbit itself and are not shown in Fig. 3 (after Young 1971).

There have been very few electrical recordings made from the CNS of cephalopods. Fine intracellular recordings from an isolated CNS preparation consisting of the subo-esophageal lobes (thought to be primarily a motor system) revealed several types of spiking and non-spiking neurones (Laverack 1980). However, it was not possible to test synaptic inputs rigorously, and as the supraoesophageal system was removed, 'learning' and 'memory' areas were not examined. Indeed, the author made no comment regarding 'plasticity' and this aspect of brain function. Later, via recordings using extracellular bipolar electrodes on restrained octopus, Bullock (1984) and Bullock and Basar (1988) reported that the supraoesophageal lobes were mostly silent, though this silence was occasionally punctuated by repetitive spiking activity which could not be driven by stimulating input tracts. In contrast, field potential recordings from the basal lobes of intact cuttlefish revealed, as expected, ongoing motor-like activity (Budelmann et al. 1995). As in the previous studies, the suproesophageal lobes were not examined.

Living brain slice technology, already being applied in the study of vertebrate brains, has long held the promise of revolutionising the analysis of cephalopod CNS function. Williamson and Budelmann (1991) first showed the utility of this approach by demonstrating that anterior lateral pedal lobe oculomotor neurones received converging inputs from the statolith and visual tracts. Later, some analysis was made of visual responses using optic lobe slices (Williamson et al. 1993). However, none of these studies looked at the cephalopod nervous system's capacity for plasticity.

Following our discovery of NMDA- and AMPA-like transmission in the chromatophore system of squids (Lima et al. 2003), we reasoned that, as in earlier work on vertebrates, it would be instructive to examine the learning and memory areas of the CNS from this point of view. For investigating the vertical lobe system of octopus (VL), a brain slice preparation was developed from sagittal vibratome slices of the vertical and median superior frontal (MSF) lobes (Fig. 4). MSF neurones input to the VL, and

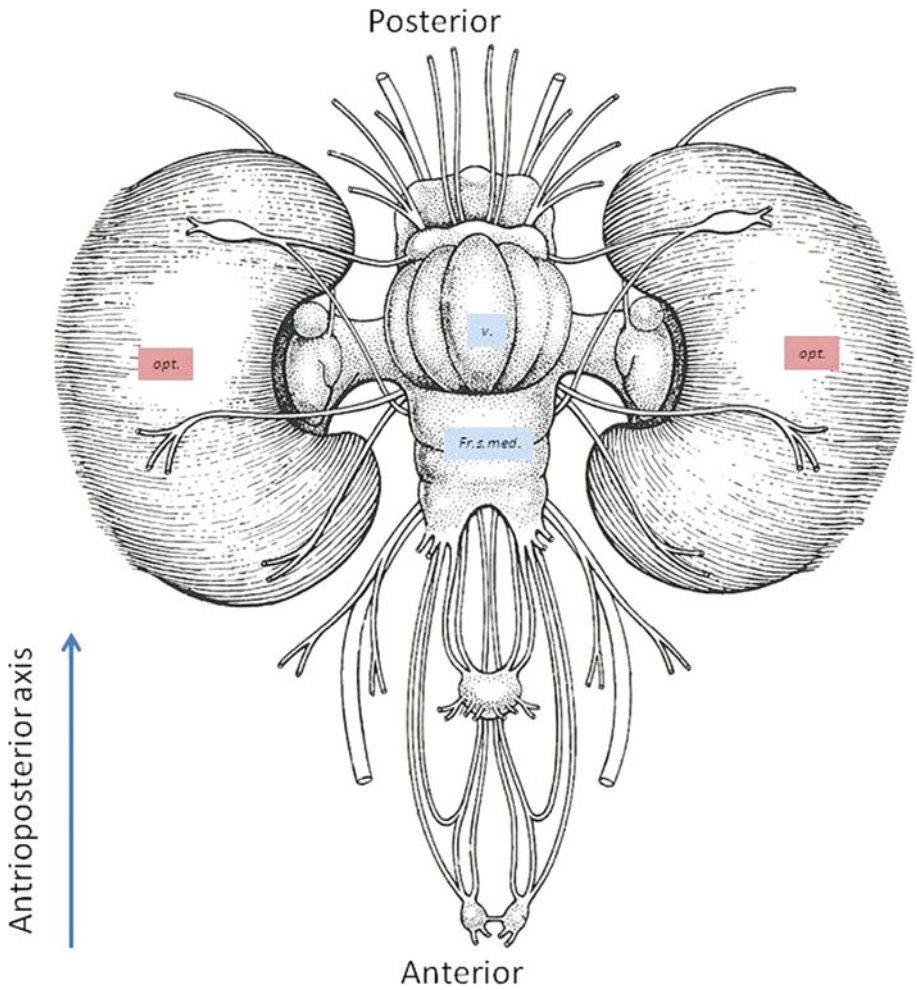

Fig. 3 Dorsal view of Octopus (*O. vulgaris)* 'CNS' showing the major lobes with those discussed in this review highlighted. *V* Vertical lobe (VL in the text), *opt.* optic lobe (OL in the text), *Fr.s. med.* Medial superior frontal lobe (MSF in the text). Adapted from Young (1971)

this preparation enabled electrical stimulation of the MSF tract and its input to the VL. We were able to record extracellular field potentials from cortical areas of the VL. These field potentials showed remarkable synaptic dynamics not reported previously in other cephalopod 'brain' areas (Hochner et al. 2003). Trains of stimuli evoked a dramatic facilitation of postsynaptic field potentials, followed by depression of more than 5–6 pulses. After such a period of synaptic stimulation, we noted a long-term increase in synaptic strength (Hochner et al. 2003). This increase was maintained in slices for periods of >12 h (Langella 2005). Here, as in the chromatophore system of squid, the main transmitter is probably glutamate or a glutamate-like substance acting on AMPA-like receptors (Hochner et al. 2003; Langella 2005). Despite the well catalogued presence of NMDA receptors in cephalopod CNS (Di Cosmo et al. 2004, 2006), neuropharmacological experiments indicated that NMDA-like receptors were unlikely to play a part in plasticity at these synapses (see Hochner et al. 2003, 2006). Later comparative work on similar learning and memory areas in cuttlefish revealed that, here, LTP occurred, but was mediated by cholinergic transmission (Shomrat et al. 2011). Thus, despite some superficial similarity of cephalopod learning networks to those of vertebrates, cephalopod networks differ significantly at the biophysical level.

The 'CNS' optic lobes

Cross-species work mentioned above has shown that synaptic plasticity is a common feature of the learning and memory areas of animals with complex nervous systems. Allowing that few regions of the cephalopod CNS have been subjected to an analysis of plasticity, is it possible that all CNS lobes exhibit use-dependent plasticity? This is a particularly interesting question, as the cephalopod optic lobes have been used to produce giant synaptosomes that have been instrumental in the study of biochemical mechanisms involved in pre-synaptic functions (c.f. protein synthesis; see Eyman et al. 2007). To examine this question further, we developed a brain slice preparation from the optic lobes of both squids and octopus. In Fig. 5, the outer layers of the lobe and the main synaptic contacts are shown

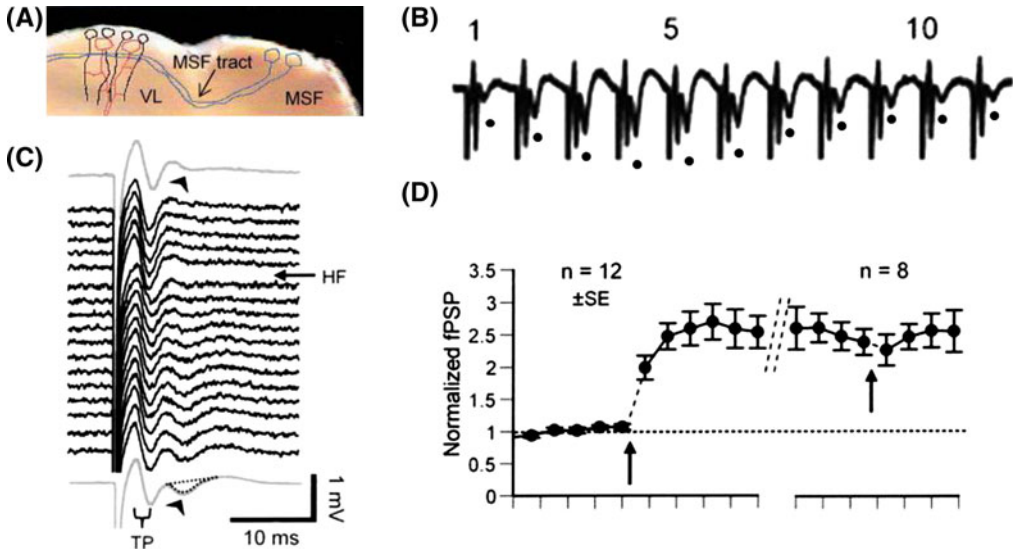

Fig. 4 Synaptic plasticity in Octopus (*O. vulgaris*) vertical lobe slices. **a** a photo of a sagittal slice showing diagrammatically MSF tract and VL. **b** Example of the results of a train of stimuli to the MSF tract recorded as a field postsynaptic potential (fPSP) from the VL. Pre- and postsynaptic field potentials are shown, with post-synaptic potentials indicated with *dots* for clarity. The fPSP can be seen to facilitate, then undergo depression during the train of pulses. **c** The effect of a train of high-frequency stimulation (HFS) on the fPSP. TP = MSF tract field potential. The *arrow* indicates the fPSP which can be seen to increase after the HFS. **d** The fPSP over time after HFS. HFS results in a significant long-term potentiation of the fPSP. Images modified from Hochner et al. (2003)

semi-diagrammatically. Field potential recordings showed distinct pre- and postsynaptic components. The postsynaptic field potential was largely monophasic and was unlike the biphasic response seen in the VL (see Fig. 5, compare with Fig. 4). This waveform is due to the fact that recording was often made near the massive synaptic terminations of the photoreceptor axons (the so-called carrot-like pre-synaptic bags). There was thus no biphasic *en passant* effect observed such as that shown in the LV. A surprising finding was that the giant terminals which had been identified as cholinergic (Florey and Winesdorfer 1968) were not excitatory, but contributed to a strong paired-pulse pre-synaptic inhibition. In other words, repetitive stimulation apparently resulted in a strong synaptic depression, but this was due to pre-synaptic modulation by inhibitory ACh receptors rather than intrinsic depression, such as that mentioned earlier. Here, excitatory transmission was likely to be glutamatergic. Long-term recording after high-frequency stimulation resulted in no increase or decrease in synaptic strength, leading us to conclude that here, there were little or no long-term changes in synaptic strength due to plasticity mechanisms (Piscopo et al. 2007).

The peripheral nervous system; the squid giant synapse

Arguably, the giant synapse of the squid is still one of the most experimentally amenable synaptic preparations with which to study chemical synaptic transmission. It has the exceptional property of allowing long-term electrical recording from both pre- and postsynaptic territories. Although the giant synapse forms part of the circuit of the escape system, and elaborate synaptic dynamics would not be expected, it was recognised, in early studies of chemical synaptic transmission, that postsynaptic responses as a result of pre-synaptic stimulation were not completely linear in the short-term (Del Castillo and Katz 1953). Indeed, facilitation of transmitter release was noted early on (Takeuchi and Takeuchi 1962). As synaptic transmission is driven by calcium ions entering voltage-gated calcium channels located on the pre-synaptic terminal, a possible explanation was that this influx could be transiently increased by increasing the activation (facilitation) of pre-synaptic voltage-gated Ca^{2+}channels. Equally, depression could be caused by a progressive inactivation of the same pre-synaptic calcium channels. Charlton and Bittner (1978a, b), by carrying out pre-synaptic voltage clamp, were able to demonstrate that during and following both facilitation and depression, there was no change in the voltage-dependent pre-synaptic calcium currents. From this finding, they concluded that facilitation was due to a build-up of residual Ca^{2+} in the pre-synaptic terminal, confirming the role proposed previously for cytoplasmic calcium in the 'residual calcium hypothesis' (Katz and Miledi 1968; Rahamimoff 1968). They also suggested that depression was due to calcium build-up leading to exhaustion of transmitter. Later work on the mammalian Calyx of Held

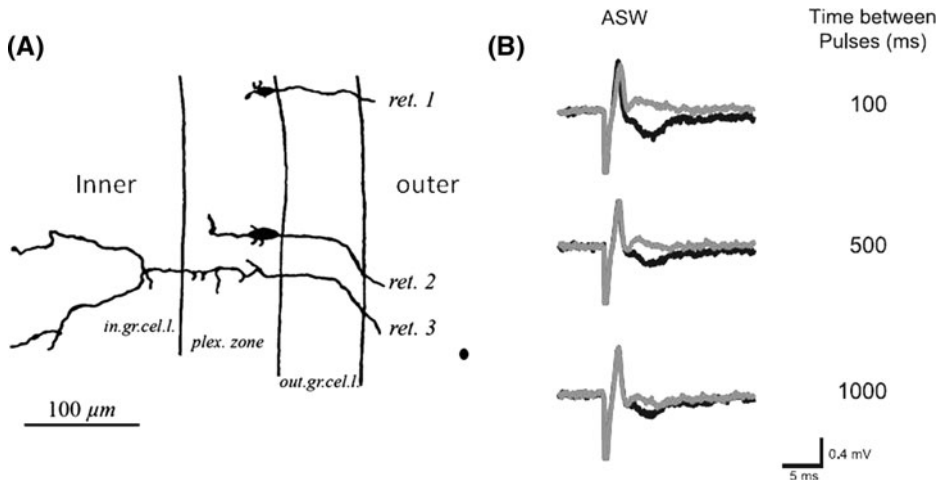

Fig. 5 Synaptic transmission in octopus (*O. vulgaris*) optic lobe (OL) slices. **a** Diagram showing that there are three types of photoreceptor synapses made in the cortex of the optic lobe. Ret 1, 2, and 3—type photoreceptor terminals which form synapses in the outer, outer and middle, and inner portions of the plexiform layer. The majority of terminals are Ret 1 and 2 and have giant bag-like pre-synaptic terminals. **b** Recordings made from the plexiform layer. Both pre- and postsynaptic field potentials can be seen. Two traces are superimposed to illustrate the time course of the pre-synaptic inhibition of the postsynaptic field potentials. As the time is increased between pulses, the inhibition on the second trace (*grey*) is gradually removed. Modified from Piscopo et al. (2007)

[a giant synapse that also permits pre- and post-synaptic recording (Forsythe 1994)] showed that at least in the mammalian CNS, there is a facilitation of the pre-synaptic current which contributes to postsynaptic facilitation (Cuttle et al. 1998). Thus, facilitation in the squid giant synapse is markedly different from that in the vertebrate CNS. As far as depression is concerned, manipulation (e.g., lowering) of postsynaptic Ca^{2+} by injecting EGTA or BAPTA massively relieves fatigue during trains of trans-synaptic stimulation (Vinogradova et al. 1999, 2002). So, it would seem unlikely that transmitter depletion accounts entirely for the depression.

The peripheral nervous system; the giant axon

Axons are not usually considered as elements that exhibit use-dependent plasticity, as they have the job of conducting action potentials in an all-or-none manner. The giant axon, however, has been studied in great detail, and here, there are indications of short-term changes in action potential shape that could have implications for signalling. The axons' normal communication with the mantle muscle may consist of the transmission of a single action potential (as shown by Prosser and Young 1937). But in fact, it was observed that several action potentials may be used in the living animal at relatively high frequency (Otis and Gilly 1990) to augment the force of mantle muscle contraction (Brown and Bone 1991; Bone et al. 1995). There are considerable effects on action potential shape due to peri-axonal K^+ accumulation around the axon at 40 Hz firing frequencies (Frankenhauser and Hodgkin 1956; Clay 1986; Inoue et al. 1997). These changes are due to a gradual decline in the amplitude of the action potential undershoot and, in extreme cases (e.g., axon damage), a decrease in the positive potential generated by the Na^+ current (Abbott et al. 1988; Brown 1993). Although the observed changes in action potential shape are small, any change in potential at the pre-synaptic terminal may alter the quantity of transmitter released. Indeed, an effect of K^+ accumulation has been noted at the giant synapse where local accumulation of K^+ may significantly reduce the amount of transmitter released during artificial trans-synaptic stimulation (Weight and Erulkar 1976; Erulkar and Weight 1977). However, a safety factor 'built-into' the giant axons and synapse ensures that transmission is faithfully 1:1 over relatively large ranges of extracellular K^+ in vivo. For example, as 'naturally' produced action potential trains consist of only 2–3 action potentials at 40 Hz (Otis and Gilly 1990), and as synapses are capable of passing around 45 artificially stimulated postsynaptic APs before post-synaptic potentials fall below the amplitude sufficient for the generation of post-synaptic action potentials (Vinogradova et al. 2002), the small changes seen during activity at both synapse and axon are well within the safety factor window for high-fidelity (1:1) signalling.

Although the third-order giant fibre system shows little plasticity, some remarkable work carried out on the development of the control of escape jetting in newly hatched squid shows that there is a 1–2-week 'plasticity window' where the capacity to control escape vs feeding behaviour may be set up. Squid fed difficult-to-catch prey

(copepods) developed the capacity to exert inhibition over escape jetting during feeding, while animals fed an *Artemia* diet failed to develop this capacity. The artemia-fed animals failed to acquire this capacity if fed copepods later in ontogeny (Preuss and Gilly 2000). This inhibition may relate to the so far unexplained presence of inhibitory transmission at the giant synapse (Stanley 1989; Vinogradova et al. 1999) and the possible inhibitory modulation of glutamate receptors (Brown et al. 2007). This is perhaps a rare example in invertebrates of a 'critical period' (see Kandel 1985).

The peripheral nervous system; the neuromuscular; and chromatophore systems

Cephalopods are highly 'neural' animals. Their powerful mantle (Bone et al. 1994), arm (Matzner et al. 2000), and chromatophore muscles (Florey and Kriebel 1969) are all innervated and amenable to postsynaptic recording, and synaptic dynamics have been noted in preparations of each of these structures.

Chromatophores are the organs in the skin of cephalopods that enable them to rapidly change 'colour' and overall body patterning. Each chromatophore consists of a pigment sac connected to an array of radial muscle fibres ($n = 20$–25) which are directly innervated by nerves that run monosynaptically from the chromatophore lobes in the brain (Messenger 2001). The main neuromuscular transmitter is glutamate (Bone and Howarth 1980; Florey et al. 1985), and oddly, postsynaptic receptors across the skin are AMPA-like, though in the dorsal part of the skin both AMPA (2-amino-3-(3-hydroxy-5-methyl-isoxazol-4-yl) propanoic acid) and NMDA (*N*-methyl-D-aspartic acid)-like receptors coexist (Lima et al. 2003). Along with evidence for 5-HT (5-hydroxytryptamine, Florey and Kriebel 1969), nitric oxide (Mattiello et al. 2010), and peptidergic (Loi et al. 1996) modulation of transmission, this preparation offers interesting experimental opportunities (Packard 2006). Indeed, the synaptic dynamics in ventral and dorsal cephalopod muscle are different. Dorsal neuromuscular transmission shows both facilitation and short-term potentiation (Florey and Kriebel 1969; Lima et al. 2002), whereas ventral neuromuscular transmission does not. It is interesting to note that dorsal and lateral chromatophores are most frequently used in the production of complex body patterns (Lima et al. 2003), so it would seem that in this case, synaptic plasticity is used not for learning and memory, but for signalling to conspecifics and camouflage/ambush.

The neuromuscular junctions of the arms have also been subjected to detailed biophysical analysis. The arms are of particular interest neurobiologically, as they contain a large number of nerve cells and ganglia (Young 1971) and can be operated in a semi-autonomous fashion (Sumbre et al. 2005). Unlike the mantle muscles, the main excitatory transmitter here is likely to be acetylcholine (ACh, Matzner et al. 2000). Three different excitatory nervous inputs were noted for each muscle cell: two low quantal amplitude signals (1–5 mV with rise times of 4–15 ms) and one of high quantal amplitude (5–25 mV with fast rise times 2–4 ms). As the muscle fibres are electrotonically compact, the expected responses would be almost stochastic. Very modest activity-dependent plasticity was noted, as expected for a fast motor synapse (Matzner et al. 2000).

Conclusions

Considering the fascinating behaviour of cephalopods and the size and complexity of their nervous systems, it is remarkable that we know so little about plasticity mechanisms at cephalopod synapses. At this point, we may conclude that (1) use-dependent long-term changes due to plasticity is seen distinctly in only two areas, the supraoesophageal lobes and the remarkable skin-located chromatophore system; and (2) in other parts of the CNS, short-term synaptic dynamics are present, but plasticity does not produce long-term changes. Thus, as in vertebrates, dynamic synaptic plasticity is located in areas that are involved in learning and memory. However, it is notable that in cephalopods, the unique chromatophore system also recruits synaptic dynamics in animal–animal signalling. At present, the experimental work mentioned here has, at best, only scratched the surface of the problem. No cellular or mechanistic analysis of the underlying mechanisms has yet been possible at the synaptic level, and much work remains to be done.

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Conflict of interest None.

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