

The fish: What potential for awareness?

C-fibres, cognition and consciousness

Dr Colin Johnston

MAF Biosecurity New Zealand
Investigation & Diagnostic Centres
Upper Hutt, New Zealand

Introduction

Of all the questions regarding conscious awareness in fish, the question of pain sensation is one which has dominated over the last few years. It seems appropriate, therefore, to use this as a model to discuss the wider aspects of cognition and consciousness in teleost (bony) fish.

We have a reasonably good understanding of pain sensation and associated neural pathways in humans. This has been derived through neurophysiology experiments, the unfortunate results of trauma or disease in the central nervous system, psychiatric pharmacology, neurosurgery and modern techniques such as functional magnetic resonance imaging and positron emission tomography.

One can examine the relevant literature on the neuroanatomy of teleost fish as regards nociception, and one can examine studies designed to demonstrate its functionality. However, despite general agreement on the nociceptive properties and functional framework in teleost fish there remain robust arguments for and against the likelihood of true pain sensation.

It is necessary to look higher; at the diencephalon (midbrain) and telencephalon (forebrain) for further inspiration, and perhaps some food for thought in the wider areas of cognition and consciousness.

The nociceptive functional unit in mammals

Readers are directed to useful reviews of the neuroanatomy of pain (Price 1999; Almeida et al. 2004), although there are many equally useful reviews available. A brief and very simplified description follows.

Specially adapted free nerve endings in the dermis respond to noxious stimuli, such as pressure or heat, producing action potentials in their associated thin, myelinated A δ -fibres or even thinner, unmyelinated C-fibres. These afferent neurones pass to the dorsal horn of the spinal cord where they link with spinal reflex arcs as well as passing fibres to the spinothalamic tracts in the contralateral ventral white matter. The afferent neurones from the nociceptors utilise Substance P (P for pain) as a neurotransmitter. There are numerous μ -opioid receptors associated with the afferent neurones and their associated spinal pathways.

The spinothalamic tracts ascend the spinal cord to the brain. Neurones radiate to the reticular formation and periaqueductal grey in the hindbrain, and the thalamus in the midbrain. All of these structures, from the midbrain and hindbrain to the free nerve endings in the skin form what can be called the nociceptive functional unit.

The thalamus has an intricate network of connections to forebrain (cortical) structures. These include connections from lateral thalamic nuclei to the somatosensory cortex and connections from the medial thalamic nuclei to other cortical regions such as the anterior cingulate gyrus, frontal cortex, posterior parietal lobe, insula, amygdala and hippocampus. Connections with some cortical areas, such as those with the cingulate gyrus and parietal lobe, generate

the emotional aversiveness of pain and an awareness of body integrity respectively and are recognised to be involved in the conscious awareness of the noxious stimuli. Some, however, such as those to the somatosensory cortex, are not explicitly linked with conscious awareness.

Ascending nociceptive impulses entering the periaqueductal grey will stimulate a range of further radiations within the brainstem, medulla and pons. Descending signals pass to the *locus coeruleus* and the *nucleus raphe magnus*, from which noradrenergic and serotonergic neurones descend the spinal cord, via the reticulospinal tract, and inhibit activity associated with the afferent A δ - and C- fibres. In addition, the periaqueductal grey radiates to the rostral ventrolateral medulla (RVLM), where it induces changes in the cardiovascular system via the sympathetic nervous system, and the *nucleus retroambiguus*, which induces innate behavioural changes such as vocalisation, grimacing and locomotor responses. The periaqueductal grey is rich in μ -opioid receptors, which increase the descending inhibition of nociception.

Nociception in fish

We know that teleost (bony) fish possess nociceptors similar to mammals (Sneddon et al. 2003a), that these receptors derive from afferent spinal nerves that innervate the spinal cord (Rose 2002), and that they consist of A δ - and C- fibres (Sneddon et al. 2003a, Dunlop & Laming 2005).

Similarly to mammals, there is evidence to suggest that fish possess the functional equivalents of the spinothalamic and reticulospinal tracts (Snow et al. 1993), as well as medullary structures such as the periaqueductal grey, *locus coeruleus* and reticular formation (Sneddon 2006).

Neuroactive chemicals identified in fish include Substance P, enkephalins and β -endorphins. In addition, fish possess, amongst others, μ -opioid receptors (FSBI 2002; Hastein 2004).

Everyone seems to be in agreement that teleost fish possess the basic functional unit of nociception, including the inhibitory feedback components, found in mammals.

Numerous studies have demonstrated the response of teleost fish to μ -opioid receptor agonists such as morphine. Morphine ablated the adverse responses seen following the injection of noxious substances into the lips of rainbow trout (*Oncorhynchus mykiss*)

(Sneddon 2003), it rekindled the “fear” of a novel object in trout whose attention was apparently distracted by the noxious effects of acetic acid injections in their lips (Sneddon et al. 2003b), and it stopped goldfish responding aversively to electric shocks. The opioid antagonist, naloxone, reversed this effect in the same fish (Ehrensing et al. 1982).

The argument is commonly made that, if fish did not feel pain, why would they have similar nociceptive pathways to mammals, use the same neurotransmitters as humans and have an apparently identical response to morphine (FSBI 2002; Hastein 2004)?

It is not an unreasonable assertion. It is hard, however, to state with absolute certainty that it is true. It can be argued that the nociceptive functional unit is just that; a neuroanatomical pathway that functions in the periphery, the spinal cord and the lower levels of the central nervous system and does not necessarily impinge upon consciousness. Neurotransmitters are just neurotransmitters; there are a finite number of chemicals available in the nervous system and they may fulfil multiple roles. Finally, one can argue that μ -opioid agonists, like morphine, have a negative feedback role in nociception via the receptors in the periaqueductal grey and spinal cord, rather than having a purely analgesic function.

In examining the literature it is clear that there is general agreement of the functioning of nociceptive systems in teleost fish at levels below the forebrain, but that there is also general disagreement above this level.

Anthropomorphism and the necessary neocortex

One school of thought is that humans, instinctively, anthropomorphise animals, projecting our mental processes and abilities onto lower order animals, and that a detached, subjective look at the forebrain, or telencephalon, of fish is needed (Rose 2002; Iwama 2007).

In this school of thought consciousness, and its associated awareness, is a function of a massively expanded neocortex. An examination of the fish brain is enough to show that there is, indeed, a very small cortex. It has therefore been hypothesised that fish do not have a complex enough brain structure to allow higher processing and consciousness (LaChat 1996; Rose 2002).

The philosophical and theoretical justifications for this hypothesis are numerous (Rose 2002, 2007).

Patients in a persistently vegetative state (PVS) have been used as examples of the necessity for the neocortex in the generation of consciousness. The argument goes something along the lines that, given a noxious stimulus these PVS patients can respond with behaviours that appear to be pain responses such as grimacing and pushing away the stimulus; however, they have no consciousness and are not aware of pain. Thus innate behavioural responses are not evidence of pain sensation, and the cortex is a strict requirement for conscious awareness (Rose 2002).

One study in fish involved the ablation of the telencephalon (Overmier & Papini 1986). It was reported that the experimental subjects could find and eat food, participated in social behaviours (such as schooling, spawning and intraspecies aggression), courtship, nest building and parental care. Avoidance learning was still possible in these fish. Although, readers should note that it was clearly much more difficult to develop avoidance learning behaviour without a forebrain (Overmier & Papini 1986).

It is the contention of this school of thought that there are no areas of the fish brain of sufficient complexity, to replace the neocortex, that are not already committed to other functions (Rose 2002).

In addition, the neocortical argument contends that avoidance learning, or fear conditioning, is an example of implicit learning (or procedural representation) and requires no conscious awareness. Indeed, the ability to learn is observed in all vertebrates, even decerebrate ones (McPhail 1998).

The alternate school of thought is, obviously, that consciousness is possible. It is necessary to try and work through some of the thinking and evidence for this alternative position.

First indications of more complex cognition

So, how can we progress this conundrum? Can we look beyond what can be argued to be innate behavioural responses? In other words, what is the likelihood of higher processing and at least some form of consciousness in teleost fish?

Firstly, extra-cortical processing happens in other species: The optic tectum (midbrain) of birds, rather than the optic cortex, is used to process visual stimuli (FSBI 2002). Does something similar happen in fish?

There is certainly evidence to suggest that apparently advanced cognitive functions can be carried out in the fish brain, regardless of the amount of cortex.

Goldfish can learn mazes (Rodriguez et al. 1994), butterfly fish navigate coral reefs using landmarks (Reese 1989) and gobies learn the layout of rockpools at high tide so that, if threatened at low tide, they can jump out of an isolated rock pool into a neighbouring one (Aronson 1971). Paradise fish are reported to avoid the areas where they have previously encountered a predator (Czanyi & Doka 1993). These all indicate the ability to build mental representations of their environment, a reasonably complex task.

Guppies (*Poecilia reticulata*) learn the route to food by shoaling with more knowledgeable conspecifics. The inexperienced fish show a preference for shoaling with familiar fish that are experienced (Swaney et al. 2001). This demonstrates conspecific recognition. Conspecific recognition, arguably a complex skill, is also demonstrated by the Australian seahorse (*Hippocampus whitei*), which form pairs that mate repeatedly and exclusively. The pair greets each other daily and eschews interactions with non-partners (Vincent & Sadler 1995).

Carp have been shown to avoid hooking following catch-and-release (Beukema 1970), although, there are also reports of fish being repeatedly hooked in other studies (Schill et al. 1986; Behnke 2004).

In addition, published studies demonstrate that areas of the fish telencephalon have functionally homologous properties to areas of the mammalian cortex. Areas of the medial and lateral pallium of the telencephalon have been linked to the functions of the amygdala and hippocampus (both components of the cortex) in humans (Portavella et al. 2004). It has been hypothesised that the difficulty in learned avoidance behaviour in fish subject to telencephalic ablation, reported earlier (Overmier & Papini 1986), suggests that one function of the fish telencephalon could be to use emotional states as conditioned reinforcers to drive instrumental responses i.e. the consequences modify the behaviours.

Consciousness: Structure or process?

Consciousness may be primary or secondary. Primary consciousness is the ability to generate a mental scene in which diverse information is integrated for the purpose of directing oneself. Secondary consciousness is

taken to mean a higher order cognition incorporating self knowledge and self awareness (Edelman & Tononi 2000).

Rather than being tied to a specific anatomical type of structure, e.g., a six-layered neocortex, it is now considered more likely that consciousness is related to functional interactions between brain structures, especially the thalamus and the cortex (Edelman & Tononi 2000; Laureys et al. 2000; Baars 2002), the so-called thalamocortical networks.

There have been reports of functionally normal individuals who display apparently normal consciousness and IQ levels but lack the normal degree of neocortical expansion (Edelman & Tononi 2000). It has also been demonstrated that a persistent vegetative state (PVS) may result from damage to thalamic nuclei, even when accompanied by almost normal metabolic rates in the cortex (Schiff et al. 2002). Positron emission tomography studies have shown decreased connectivity between the thalamic nuclei and both the anterior cingulate gyrus and prefrontal cortex in patients in a PVS. Those that have recovered from a PVS show a restoration in thalamocortical activity (Laureys et al. 2000), suggesting that the restoration of consciousness is associated with the restoration of the functional relationship between the thalamus and the cortex.

So, historically perhaps, we have tended to equate a loss of conscious awareness with cortical damage. However, given the evidence above, this conclusion is likely to be erroneous. If we consider the human brain for a moment, we have a model of both conscious and unconscious states in the same individual. No one would deny that there is a significant difference in our level of consciousness between being awake and active and being in a deep dreamless sleep, with no feeling of self-awareness. There is no physical difference between our brains in these two very different conditions and so perhaps we can conclude that the difference between the presence and absence of conscious awareness can be solely a functional one (Llinas et al. 1998).

The requirement for the functional interaction of thalamic and cortical structures in the generation of consciousness has led to the idea of the so-called dynamic core hypothesis (Edelman & Tononi 2000; Laureys et al. 2000; Baars 2002).

The Dynamic Core Hypothesis: Resonance networks and γ -frequencies

γ

The functioning of the thalamocortical neural networks in the generation of consciousness can be studied using a variety of techniques. Magnetoencephalopathy and some more invasive studies in cats have indicated that consciousness is supported by what is termed neural resonance in thalamocortical structures via feedback loops, or so-called neural signal re-entry. Importantly this resonance seems to be in the γ -frequencies (20–50 Hz) with most effective activity and greatest signal amplification in the feedback loops at about 40 Hz (Llinas et al. 1998).

Thalamic neurones intrinsically display rhythmic, oscillatory activity in the γ -range of frequencies. This activity is greatest in their dendritic processes (those that make connections with other nerve cells) and occur at highest frequency (around 40 Hz) when depolarised to <-45 mV (Llinas et al. 1998).

The state of being awake is associated with thalamic neurone depolarisation and associated strong resonance in γ -frequencies, whereas, deep dreamless sleep is associated with thalamic neurone hyperpolarisation, which appears to inhibit the oscillatory activity of the thalamic neurones (Llinas et al. 1998) and hence greatly reduced resonance in the thalamocortical networks.

Extrinsic stimulation of the thalamocortical networks at a frequency of 40 Hz induces distinct thalamocortical resonant columns separated by active inhibition via GABA (γ -amino butyric acid)-mediated inhibitory neurones. Stimulation of cortical neurones, or activity in the network at lower frequencies (such as 10 Hz), produces widespread but undirected activity across the thalamus and cortex, similar to that seen in deep, dreamless, slow wave sleep (Llinas et al. 1998).

This suggests that the stimuli that we become consciously aware of are processed in thalamocortical resonant columns (40 Hz frequencies ideally), with each distinct stimulus being processed in independent units or loops of neurones.

In summary, the generation of consciousness is less dependent on the neuroanatomy of the cortex, and more dependent on the existence of thalamocortical networks of neurones that form resonant feed-back loops. The frequency of the oscillatory activity in these resonant loops is important in the

generation of discriminatory resonant columns. Stimuli that induce thalamic and cortical activity at frequencies outside the γ -frequencies would fail to generate resonant columns and thus the stimuli may well induce cortical activity at a level that we would not necessarily be aware of.

Thalamocortical networks in teleost fish

Can we determine how far the central nervous system of fish satisfies the requirements of the dynamic core hypothesis?

There is adequate experimental evidence to indicate that teleost fish do possess thalamocortical neural networks. These neural pathways have been elucidated for, amongst others, visual somatosensory processing (Ito et al. 1986), olfactory processing (Laberge & Hara 2001) and vocal/acoustic activity (Goodson & Bass 2002).

Does the presence of these proven thalamocortical neural networks prove that there is conscious awareness, or that noxious stimuli are processed similarly?

While the presence of thalamocortical neural networks is considered a necessary component of the dynamic core hypothesis, we have seen previously that it is more complicated than that. So, perhaps we can say it is evidence of complex neural structures in the fish brain but that we need to look further, especially as regards the higher processing of nociceptive inputs.

Do nociceptive stimuli radiate beyond the thalamus in fish?

Goldfish and trout were studied to try and answer this question. Fine electrodes were placed in the spinal cord, cerebellum, tectum and telencephalon of the fish and a polymodal nociceptor was individually stimulated electrically. The resultant neural activity was measured in the different areas of the nervous system and could be classified into responses via A δ -fibres and C-fibres. The results were very clear; stimulation of an individual nociceptor resulted in neural activity of both A δ - and C-fibre characteristics in the telencephalon (forebrain) of both goldfish and trout. Goldfish demonstrated much more C-fibre mediated activity than trout, in which A δ - activity predominated (Dunlop & Laming 2005). This indicates that there must be neural projections from midbrain structures, that receive nociceptive inputs, to the cortex of fish.

There thus appears to be a nociception-linked thalamocortical neural network.

A separate corroborative study used functional magnetic resonance imaging to study brain activity in fish during stimulation of nociceptors. The fMRI indicated that there was activity in the midbrain, which is only to be expected, and in the forebrain (Sneddon 2006). In addition, the same researchers noted increased gene expression in the forebrain in response to noxious stimuli (Sneddon 2006). This is significant, perhaps, because it is known that Substance P (the neurotransmitter associated with C-fibres) can up-regulate the expression of immediate early genes for example, as part of a long-term stress response. This would again indicate that nociceptive stimuli are radiated to the fish forebrain.

It is apparent now that noxious stimuli induce both neural activity and gene expression in the forebrain of fish. Still, this is not necessarily evidence of conscious awareness of those stimuli. After all, we have seen that the frequency of resonance in thalamocortical networks can be the difference between conscious and unconscious cortical activities. Further experimental work is obviously needed.

Seeking further evidence: Cognitive theory and observed behaviours

From a psychological aspect one can consider two theorised mental states: Conscious cognition and motivational affective states.

Conscious cognition has been defined as the ability to retain learned information as mental representations, and relies on the presence of primary consciousness (Heyes 1993; Dickinson & Balleine 1994).

Mental representations may be either procedural or declarative. Procedural representations are exemplified by stimulus-response behaviours, also called implicit learning. These representations are mainly unconscious (Rose 2002), although it doesn't rule out conscious involvement. Declarative representations are more interesting. They mean that the individual is paying selective attention to internal and external stimuli and comparing them with expectations to drive flexible behaviour, or adaptive responses (Heyes 1993; Dickinson & Balleine 1994).

We can cite examples where fish have displayed apparent declarative representation; that is, they have adapted their behaviour in accordance with

expectations and observations. Siamese fighting fish, given the opportunity, will spend a greater proportion of their time observing the interactions between two other males, and when introduced to either of the fish they have been observing appear more willing to fight a fish they have seen lose an interaction than those they have seen win (Oliveira et al. 1998). When their experiences are manipulated, with apparent interactions being observed, one can reverse this effect. This behaviour is not limited to fighting fish; female songbirds (great tits) demonstrate similar behaviour (McGregor et al. 2001). Female fighting fish also display a preference to mate with males they have observed win an interaction with another male and will alter their mate choice after observing an interaction (Doutrelant & McGregor 2000).

Motivational affective states

Examples of motivational affective states are fear, hunger and thirst. They are biological adaptations designed to motivate behaviour in situations where a flexible response would be more effective than a rigid reflex response. In tetrapods and bipeds, motivational affective states are also involved in memory and learning (Chandru et al. 2004).

Two central nervous systems are thought to be involved in the development of motivational affective states; namely the limbic system and the dopaminergic neural system. Both of these are considered relatively primitive parts of the central nervous system and conserved through evolution (LeDoux 2000).

The limbic system

In humans the limbic system is formed mainly from the amygdala and hippocampus, together with input from the hypothalamus, habenulae and mammillary bodies. A number of studies involving ablation of specific areas of the teleost fish telencephalon have demonstrated functionally equivalent areas in the fish brain to the human amygdala and hippocampus (Salas et al. 1996; Portavella et al. 2002; Portavella et al. 2004). The medial pallium of the fish telencephalon has been linked to amygdalar functions (Portavella et al. 2004), whilst the lateral pallium has been equated with the hippocampus (Salas et al. 1996; Portavella et al. 2004).

The amygdala is involved in emotional behaviours and emotional memory. Lesions in the amygdala appear to abolish acquired conditioned responses

(Portavella et al. 2004). The hippocampus is implicated in spatial learning, relational memory and the processing of temporal attributes of stimuli (Portavella et al. 2004), as well as being linked to memory and declarative representation (Eichenbaum 1997). If lesions in the areas of the fish telencephalon considered homologous to the amygdala and hippocampus produce similar effects to lesions in mammals, one can theorise that fish may well have some degree of emotional memory, relational memory and declarative representation.

The dopaminergic system

The dopaminergic neural system is made up of mesolimbic and mesostriatal neurones. The mesolimbic neurones project into the limbic system and mediate learning and reward (e.g., cost/benefit). The mesostriatal neurones are linked with the substantia nigra in humans and are involved in behaviour and movement. There is experimental evidence that similar dopaminergic systems exist in teleost fish. The dopamine agonists, apomorphine and amphetamine, can be used to alter a fish's state of affect in a similar way to humans (Lett & Grant 1989; Mok & Munro 1998).

C-fibres in fish, which produce Substance P, can also be found in the same regions as the dopaminergic neurones are located. Apart from acting as a neurotransmitter in the nociceptive system, Substance P has been implicated in learning, memory and reward similarly to the dopaminergic system. Substance P has been shown to facilitate learning and reward behaviours in goldfish (Mattioli et al. 1995; Mattioli et al. 1997; Santangelo et al. 2001).

It is also possible to induce changes in the neurochemistry and behaviour of fish that faithfully mirror those seen in humans with Parkinson's disease. The chemical MPTP (1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine) targets and destroys the mesostriatal dopaminergic neurones in the substantia nigra in humans and equivalent neurones in fish, resulting in similar effects in both, namely greatly reduced dopamine and noradrenaline levels and a 90% reduction in activity levels (Pollard et al. 1996).

Experimental evidence for limbic and dopaminergic behaviours

Theoretically, fish display evidence of a functional dopaminergic system. They also appear to have a

limbic system functionally similar to mammals. So, can one design an experiment to demonstrate activity in the limbic and dopaminergic systems?

One such experiment (Dunlop et al. 2006) aimed to demonstrate an adaptive or flexible response to a stimulus as evidence of potential declarative representation, which is associated with conscious cognition and the limbic system (Heyes 1993; Dickinson & Balleine 1994; Eichenbaum 1997). The researchers then used a conspecific to introduce the potential additional aspect of reward-mediated behaviour or cost/benefit analysis; a function of the dopaminergic system.

The researchers designed a system whereby they could stimulate a discrete small area of skin nociceptors in goldfish and trout at increasing voltages along a tank. The tank was divided into four main regions set at zero volts (end), zero volts (inner), 3 volts and 30 volts (2.5 volts and 25 volts for trout). The goldfish and trout were exposed to this on two consecutive days, first in the absence, then in the presence of a conspecific held (unstimulated) in the region of highest voltage. Blood cortisol levels were measured daily.

There was a clearly graduated response for goldfish (measured in terms of escape time from each voltage area) across the voltage range and between the two days. The inverse relationship displayed between voltage and escape time could be an expression of elastic behaviour, but could also be simply due to intensity of stimulus affecting a reflex behavioural response. On the second day of the experiment, escape times were significantly reduced for each voltage area when compared with the first day. Was this evidence of learning and using expectations to adjust responses? Might we associate this change with declarative representation? Or is it just a conditioned response? A similar response was noted in trout at higher voltages but there was little difference in escape response at the lower voltages in trout.

Without a conspecific the goldfish tended to move as far away from the area of electrical stimulation as the tank would allow (to the zero volt end section). When a conspecific was introduced, the behaviour changed. The goldfish were slightly slower to leave the area of voltage stimulation (3 volts) than in the absence of a conspecific. They also tended to remain as close to the conspecific as possible (in the zero volt inner section) without entering the area of electrical stimulation. Trout were quite different; they

preferentially moved into the medium voltage section to be as close to their conspecific as possible. Was this evidence of cost/benefit decision-making in the goldfish and trout? Can it be linked to the dopaminergic system? Or is there innate shoaling behaviour in trout that is stronger than an escape response?

Interestingly, despite the goldfish remaining in the zero voltage area of the tank, their cortisol levels were significantly higher when the conspecific was present. Were the goldfish stressed by the choice between avoiding the noxious stimulus and being in close association with a conspecific? Is this evidence of limbic and dopaminergic activity?

The trout, despite being in an area of noxious stimulus (2.5 volts) had lower cortisol levels in the presence of a conspecific. Did they derive a reward from the social interaction that outweighed the noxious stimulus? Is this dopaminergic behaviour in action?

Conclusions, or just beginnings?

So, what can we say? Perhaps a summary of where I have reached is required.

Teleost fish possess a functional nociceptive system consisting of nociceptors, A δ - and C- fibres, spinal tracts, midbrain nuclear involvement and neurotransmitters.

Teleost fish respond to μ -opioid agonists, e.g., morphine. This could be due to analgesia or negative feedback on the nociceptive system.

Teleost fish display complex behaviours associated with learning, memory and spatial relationships.

Teleost fish display thalamocortical connectivity.

Consciousness, as we understand it, is more a function of resonant thalamocortical networks than the structural presence of a cortex.

However, resonance frequency is apparently critical in determining conscious or unconscious cortical activity. We know both happen in humans, so what happens in fish?

Noxious stimuli radiate beyond the thalamus in teleost fish, inducing activity in cortical C-fibres and A δ -fibres, as well as inducing gene expression in the fore brain.

Fish seem to display evidence of declarative representation (elastic responses), e.g., Siamese fighting fish. This suggests primary consciousness (as previously defined) and a functional limbic system.

Evolutionary and experimental evidence suggests that teleost fish possess functional equivalents of the limbic and dopaminergic nervous systems—systems that are linked with emotion, memory, spatial relationships, primary consciousness, reward and cost/benefit decision-making.

The appreciation or awareness of stimuli in fish may well be different to ours and it is hard for us to conceptualise a very different way of thinking or processing information, but current knowledge presents to us a range of possibilities. We don't currently know if fish thalamocortical networks operate, or support, resonant neural signal re-entry, or how important that might necessarily be. It is apparent that noxious stimuli induce gene expression in the forebrain of fish. In mammals, Substance P is also linked with increased gene expression and chronic stress.

It therefore behoves us, where possible, to give these complex animals the benefit of the doubt when it comes to their welfare. What we can say with certainty is that, regardless of the opinion on consciousness, most commentators agree that chronic noxious stimuli are a cause of stress in fish and as such represent poor welfare.

References

- Almeida, T. F.; Roizenblatt, S.; Tufik, S. 2004: Afferent pain pathways: a neuroanatomical review. *Brain Research* 1000(1-2): 40–56.
- Aronson, L. R. 1971: Further studies on orientation and jumping behaviour in the Gobiid fish *Bathygobius soporator*. *Annals of the New York Academy of Science* 188: 378–392.
- Baars, J. B. 2002: The conscious access hypothesis: origins and recent evidence. *Trends in Cognitive Science* 6: 47–52.
- Behnke, R. 2004: The best science. *Trout*: 59–60.
- Beukema, J. J. 1970: Angling experiments with carp: decreased catchability through one trial learning. *Netherlands Journal of Zoology* 20: 81–92.
- Chandross, K. P.; Duncan, I. J. H.; Moccia, R. D. 2004: Can fish suffer?: perspectives on sentience, pain, fear and stress. *Applied Animal Behaviour Science* 86(3/4): 225–250.
- Czanyi, V.; Doka, A. 1993: Learning interactions between prey and predator fish. *Marine Behaviour and Physiology* 23: 63–78.
- Dickinson, A.; Balleine, B. 1994: Motivational control of goal-directed action. *Animal Learning & Behavior* 22: 1–18.
- Doutrelant, C.; McGregor, P. K. 2000: Eavesdropping and mate choice in female fighting fish. *Behaviour* 137: 1655–1669.
- Dunlop, R.; Laming, P. 2005: Mechanoreceptive and nociceptive responses in the central nervous system of goldfish (*Carassius auratus*) and trout (*Oncorhynchus mykiss*). *Journal of Pain* 6(9): 561–568.
- Dunlop, R.; Millsopp, S.; Laming, P. 2006: Avoidance learning in goldfish (*Carassius auratus*) and trout (*Oncorhynchus mykiss*) and implications for pain perception. *Applied Animal Behaviour Science* 97(2/4): 255–271.
- Edelman, G. M.; Tononi, G. 2000: *Universe of consciousness: How matter becomes imagination*. Basic Books; New York.
- Ehrensing, R. H.; Mitchell, G. F.; Kastin, A. J. 1982: Similar antagonism of morphine analgesia by MIF-1 and naloxone in *Carassius auratus*. *Pharmacology Biochemistry and Behavior* 17: 757–761.
- Eichenbaum, H. 1997: Declarative memory: insights from cognitive neurobiology. *Annual Review of Psychology* 48: 547–572.
- FSBI 2002: *Fish Welfare. Briefing Paper 2, pp6-7* Fisheries Society of the British Isles, Granta Information Systems.
- Goodson, J. L.; Bass, A. H. 2002: Vocal-acoustic circuitry and descending vocal pathways in teleost fish: Convergence with terrestrial vertebrates reveals conserved traits. *The Journal of Comparative Neurology* 448: 298–322.
- Hastein, T. 2004: Animal welfare issues relating to aquaculture. Pp. 219–227 in: *Global conference on animal welfare: an OIE initiative, Paris, 23–25 February 2004*. World Organisation for Animal Health; Paris.
- Heyes, C. M. 1993: Imitation, culture and cognition. *Animal Behaviour* 46: 999–1010.
- Ito, H.; Murakami, T.; Fukuoka, T.; Kishida, R. 1986: Thalamic fiber connections in a teleost (*Sebaticus marmoratus*): visual somatosensory, octavolateral, and cerebellar relay region to the telenchephalon. *The Journal of Comparative Neurology* 250: 215–227.
- Iwama, G. K. 2007: The welfare of fish. *Diseases of Aquatic Organisms* 75(2): 155–158.
- Laberge, F.; Hara, T. J. 2001: Neurobiology of fish olfaction: a review. *Brain Research Reviews* 36: 46–59.
- LaChat, M. R. 1996: An argument in defense of fishing. *Fisheries* 21: 20–21.
- Laureys, S.; Faymonville, M. E.; Luxen, A.; Lamy, M.; Franck, G.; Maquet, P. 2000: Restoration of thalamocortical connectivity after recovery from persistent vegetative state. *The Lancet* 355: 1790–1791.
- LeDoux, J. E. 2000: Emotion circuits in the brain. *Annual Review of Neuroscience* 23: 155–184.
- Lett, B. T.; Grant, V. L. 1989: The hedonic effects of amphetamine and phenobarbital in goldfish. *Pharmacology Biochemistry and Behavior* 32: 355–356.

- Llinas, R.; Ribary, U.; Contreras, D.; Pedroarena, C. 1998: The neuronal basis for consciousness. *Philosophical Transactions of the Royal Society of London, Series B* 353: 1841–1849.
- Mattioli, R.; Aguillar, C.; Vasconcelos, L. 1995: Reinforcing properties of the neuropeptide Substance P in *Carassius auratus*: evidence of dopaminergic system involvement. *Pharmacology Biochemistry and Behavior* 50: 77–81.
- Mattioli, R.; Santangelo, E. M.; Costa, A. C. C.; Vasconcelos, L. 1997: Substance P facilitates memory in goldfish in an appetitively motivated learning task. *Behavioural Brain Research* 85: 117–120.
- McGregor, P. K.; Peake, T. M.; Lampe, H. M. 2001: Fighting fish *Betta splendens* extract relative information from apparent interactions: what happens when what you see is not what you get. *Animal Behaviour* 62: 1059–1065.
- McPhail, E. M. 1998: *The evolution of consciousness*. Oxford University Press; New York.
- Mok, E. Y. M.; Munro, A. D. 1998: Effects of dopaminergic drugs on locomotor activity in teleost fish of the genus *Oreochromis* (Cichlidae): involvement of the telencephalon. *Physiology & Behavior* 64: 227–234.
- Oliveira, R. F.; McGregor, P. K.; Latruffe, C. 1998: Know thine enemy: fighting fish gather information from observing conspecific interactions. *Proceedings of the Royal Society of London, Series B, Biological Sciences* 265: 1045–1049.
- Overmier, J. B.; Papini, M. R. 1986: Factors modulating the effect of teleost telencephalon ablation on retention, relearning, and extinction of instrumental avoidance behaviour. *Behavioral Neuroscience* 100: 190–199.
- Pollard, H. B.; Kuijpers, G. A.; Adeyemo, O. M.; Youdim, M. B. H.; Goping, G. 1996: The MPTP-induced Parkinsonian syndrome in the goldfish is associated with major cell destruction in the forebrain and subtle changes in the optic tectum. *Experimental Neurology* 142: 170–178.
- Portavella, M.; Torres, B.; Salas, C. 2004: Avoidance response in goldfish: Emotional and temporal involvement of medial and lateral telencephalic pallium. *The Journal of Neuroscience* 24(9): 2335–2342.
- Portavella, M.; Vargas, J. P.; Torres, B.; Salas, C. 2002: The effects of telencephalic pallial lesions on spatial, temporal, and emotional learning in goldfish. *Brain Research Bulletin* 57: 397–399.
- Price, D. D. 1999: *Psychological mechanisms of pain and analgesia*. International Association for the Study of Pain, Seattle.
- Reese, E. S. 1989: Orientation behavior of butterfly fishes (family Chaetodontidae) on coral reefs - spatial learning of route specific landmarks and cognitive maps. *Environmental Biology of Fishes* 25: 79–86.
- Rodriguez, F.; Duran, E.; Vargas, J. P.; Torres, B.; Salas, C. 1994: Performance of goldfish trained in allocentric and egocentric maze procedures suggest the presence of a cognitive mapping system in fishes. *Animal Learning & Behavior* 10: 108–114.
- Rose, J. D. 2002: The neurobehavioral nature of fishes and the question of awareness and pain. *Reviews in Fisheries Science* 10(1): 1–38.
- Rose, J. D. 2007: Anthropomorphism and ‘mental welfare’ of fishes. *Diseases of Aquatic Organisms* 75(2): 139–154.
- Salas, C.; Rodriguez, F.; Vargas, J. P.; Duran, E.; Torres, B. 1996: Spatial learning and memory deficits after telencephalic ablation in goldfish trained in place and turn maze procedures. *Behavioral Neuroscience* 110: 965–980.
- Santangelo, E. M.; Morato, S.; Mattioli, R. 2001: Facilitatory effect of substance P on learning and memory in the inhibitory avoidance test for goldfish. *Neuroscience Letters* 303: 137–139.
- Schiff, N. D.; Ribary, U.; Moreno, D. R.; Beattie, B.; Kronberg, E.; Blasberg, R.; Giacino, J.; McCagg, C.; Fins, J. J. et al 2002: Residual cerebral activity and behavioral fragments can remain in the persistently vegetative brain. *Brain* 125(6): 1215–1234.
- Schill, D. J.; Griffith, J. S.; Gresswell, R. E. 1986: Hooking mortality of cutthroat trout in a catch-and-release segment of the Yellowstone River, Yellowstone National Park. *North American Journal of Fisheries Management* 6: 226–233.
- Sneddon, L. U. 2003: The evidence for pain in fish: the use of morphine as an analgesic. *Applied Animal Behaviour Science* 83(2): 153–162.
- Sneddon, L. U. 2006: Ethics and welfare: pain perception in fish. *Bulletin of the European Association of Fish Pathologists* 26(1): 6–10.
- Sneddon, L. U.; Braithwaite, V. A.; Gentle, M. J. 2003a: Do fishes have nociceptors? Evidence for the evolution of a vertebrate sensory system. *Proceedings of the Royal Society of London, Series B, Biological Sciences* 270(1520): 1115–1121.
- Sneddon, L. U.; Braithwaite, V. A.; Gentle, M. J. 2003b: Novel object test: examining nociception and fear in the rainbow trout. *Journal of Pain* 4(8): 431–440.
- Snow, P. J.; Plenderleith, M. B.; Wright, L. L. 1993: Quantitative study of primary sensory neurone populations of three species of elasmobranch fish. *Journal of Comparative Neurology* 334: 97–103.
- Swaney, W.; Kendal, J.; Capon, H.; Brown, C.; Laland, K. N. 2001: Familiarity facilitates social learning of foraging behaviour in the guppy. *Animal Behaviour* 62: 591–598.
- Vincent, A. C. J.; Sadler, L. M. 1995: Faithful pair bonds in wild seahorses, *Hippocampus whitei*. *Animal Behaviour* 50: 1557–1569.