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Size matters: Management of stress responses and chronic stress in beaked whales and other marine mammals may require larger exclusion zones

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ABSTRACT

Marine mammal management traditionally focuses on lethal takes, but non-lethal (or not immediately lethal) impacts of human disturbance, such as prolonged or repeated activation of the stress response, can also have serious conservation implications. The physiological stress response is a life-saving combination of systems and events that maximises the ability of an animal to kill or avoid being killed. However, "chronic stress" is linked to numerous conditions in humans, including coronary disease and infertility. Through examples, including beaked whales and sonar exposure, we discuss increasing human disturbance, mal-adaptive stress responses and chronic stress. Deep-diving and coastal species, and those targeted by whalewatching, may be particularly vulnerable. The various conditions linked with chronic stress in humans would have troubling implications for conservation efforts in endangered species, demands management attention, and may partly explain why some species have not recovered after protective measures (e.g., smaller protected areas) have been put into place.

1. Introduction

Marine mammal management and conservation traditionally focuses on situations where animals are killed as a consequence of human interaction (known as "lethal takes" in US and other legal systems), such as in bycatch, vessel collisions and strandings. Thus, the most widely known issue related to underwater sound is that of the plight of beaked whales exposed to military mid-frequency sonar (see Parsons et al. (2008) for a review of the issue). Beaked whales that have stranded coincident with naval exercises are often found with decompression sickness- or "bends"-like lesions (Jepson et al., 2003; Fernández et al., 2004, 2005). The whales are thought to react behaviourally at sound levels well below those thought to cause 'injury' (Hildebrand, 2005), in ways that ultimately cause the lesions, mortalities and mass strandings that have been highly publicised (Cox et al., 2006; Rommel et al., 2006; Tyack et al., 2006). This hypothesis appears to be supported by the limited and preliminary, but direct, data obtained in recent studies in which cetacean diving behaviour changed in a way that might lead to injury, although the exact mechanism of action remains elusive (Moretti et al., unpublished; Tyack, unpublished). However, there is increasing concern that non-lethal impacts of human disturbance could also have serious conservation implications, indicating that the mortality counts (which are themselves likely to be substantial underestimates: see Parsons et al. (2008)) only reveal a fraction of the picture.

Possibly the most important of non-lethal (at least, not immediately lethal) impacts arises from the prolonged or repeated activation of the stress response. The physiological stress response, which is highly conserved across species, is a life-saving combination of systems and events that essentially maximises the ability of an animal to kill or avoid being killed (for detailed reviews and further information see Deak (2007) and Romero and Butler (2007)). However, it is important to note that the goal of physiological stress responses is to survive the immediate threat, not necessarily to preserve functioning for distant periods into the future. The principle systems involved are the sympathetic nervous system (SNS) and the hypothalamic–pituitary-adrenal (HPA) axis – both of which are activated immediately upon the *perception* of a threat by the animal. Within seconds, the release of adrenalin and noradrenalin (AKA epinephrine and norepinephrine) by the SNS produces numerous changes, including increases in heart rate, gas exchange and visual acuity, and a redistribution of blood to the brain and muscles and away from the stomach and other non-essential organs. Behavioural changes also result, most famously the "fight or flight" response. Mean-

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while, a chain of hormones released through the HPA axis leads to the release of glucocorticoids (GCs) from the adrenal cortex (e.g., cortisol, corticosterone), usually within 3–5 min. These induce similar changes: an increase in blood glucose and suppression of non-essential activities, such as digestion, immune activity, growth, and reproduction, although the reproductive system can, in some reproductive contexts, become resistant to inhibition by GCs (Wingfield and Sapolsky, 2003). Though GCs can also alter behaviour in context-specific ways, the effects are often more subtle in nature (as moderators of behaviour) than those observed in response to SNS activation (as direct mediators of behavioural action), as is typical for steroid hormone effects on behaviour. Nevertheless, GCs seem to play a key role in orchestration of behavioural strategy, such as inducing either hiding or abandonment of an area (see Wingfield and Ramenofsky, 1997) and alterations of exploratory behaviour in standard laboratory tasks (open field test, elevated plus maze, etc. – Veldhuis et al., 1982; Sandi et al., 1996; Canini et al., 2009). This suite of effects is thought to improve survival in the face of threat, at least in part by preparing the organism for future threats (Sapolsky et al., 2000), delaying functions that can be postponed until the danger has passed, and promoting recuperative responses after stressor termination (Deak, 2007).

However, this response can become mal-adaptive when initiated too often or for prolonged periods (Korte et al., 2005). This state of "chronic stress" is linked to numerous conditions in humans, including coronary disease, immune suppression, anxiety and depression, cognitive and learning difficulties, and infertility (see Clark and Stansfeld, 2007; Romero and Butler, 2007). In addition, *in utero* exposure to GCs via the mother and/or through mothers milk to newborns has been shown to alter the stress response itself in these neurologically-vulnerable young, leading to life-long health and psychological problems (e.g., Kapoor et al., 2006).

2. Stress responses in marine mammals

Marine mammals live increasingly in a world influenced by human action. We know that many marine mammals carry high levels of contaminant loads, which can have a range of consequences for them, potentially including prolonged activation of the stress response (see reviews by Kakuschke and Prange (2007) and Martineau (2007)). It is also highly likely that changes to habitat and prey abundance and distribution through various mechanisms ranging from both coastal and offshore development to the widespread influences of climate change will be, for certain species, detrimental and may induce stress responses as well (e.g., Stirling and Derocher, 1993).

However, probably the most underestimated mechanism for inducing a (prolonged) stress response in marine mammals is that of human disturbance, of which underwater noise is likely to be an important component (e.g., Miksis-Olds et al., 2007). In addition to simply disturbing marine mammals, exposure to noise can have a range of other impacts (e.g., Nowacek et al., 2007; Weilgart, 2007) that can trigger stress responses in-and-of themselves. For example, masking – the obscuring of signal of interest to the animal by noise – can interfere with communication (including for mating), navigation and foraging as many marine animals have evolved to supplement or replace the ineffective use of vision underwater with hearing (Bradbury and Vehrencamp, 1998; Berta et al., 2006; Jensen et al., 2008). Furthermore, noise is a particular concern because it can travel large distances underwater, especially at low frequencies (Urick, 1983), which means the 'acoustic footprint' of human activities can be considerably larger than the area over which they actually occur.

2.1. Shipping and masking

The classic example of an activity with an extensive acoustic footprint is that of shipping. There is increasing evidence that distant shipping, with some contribution from other human activities, has substantially increased low-frequency background noise throughout huge areas of oceans around the world – in some cases doubling in power each decade over the past 50 years (e.g., Zakarauskas et al., 1990; Andrew et al., 2002; Cato and McCauley, 2002; McDonald et al., 2006). This increases the likelihood of signal masking and has unquestionably curtailed communication ranges quite dramatically in low-frequency users, such as the baleen whales (see Wright, 2008) and may also be having psychological impacts, such as causing anxiety (Bateson, 2007). Communication in other species may also be masked in close proximity to shipping lanes where the higher frequency components of the noise remain above ambient levels, or by smaller craft that produce noise predominantly at higher frequencies (e.g., Jensen et al., 2008).

2.2. Seismic surveys and avoidance

Another anthropogenic sound that can travel over ocean basins, at least on occasion, is that of airgun arrays, used primarily to detect oil and natural gas deposits under the ocean floor in seismic surveys (Nieukirk et al., 2004). While less likely to mask signals of interest to marine mammals because of their short duration (although it may still occur – see Nieukirk et al., 2004), their huge source levels and high rate of repetition (see Nieukirk et al. (2004) and Madsen et al. (2006) and references therein) does mean that exposure rates can be quite high. Marine mammals have been documented to exhibit a "startle" reaction in response to seismic surveys at reasonable distances (e.g., sperm whales at 2 km; Stone, 2003), which is likely indicative of the initiation of a stress response. There have also been reports of avoidance of such surveys. For example, cetacean diversity off the coast of Brazil dropped from 1994 to 2004 during seismic survey operations, with a conspicuous decrease in 2000–2001 when there were a greater number of seismic surveys (Parente et al., 2007). However, it is hard to determine exactly what such avoidance means to the animals concerned. It may represent a number of potential situations, ranging from the possibility that avoidance may have little cost to them (as might be expected if marine mammals slightly divert their migration routes) to an indication that the exposure is too unpleasant to remain in an area of particular importance despite their need to forage or breed there (see summary by Beale (2007)). Similarly, animals that remain in important areas may either be unaffected, or so dependent on the particular habitat, source of prey, or other resource that they remain despite the disturbance and/or acoustic assault, the latter of which may actually be the most stressful of the possibilities (Beale, 2007).

2.3. Whalewatching and energy budgets

Concern over the possible effects of whalewatching on marine mammals has increased over recent years, especially as information about the long-term impacts are beginning to become available (see Lusseau and Bejder, 2007). Unlike the other activities discussed above, whalewatching actively targets marine mammals meaning that disturbance can, in some cases, reach quite high levels. Cetaceans may begin to avoid certain areas if the disturbance reaches a certain threshold or if there is little cost to abandoning that location (Lusseau and Bejder, 2007). However, those that stay must contend with the consequences of attention from whalewatching vessels, which can include, but are not limited to, feeding and resting disturbance, masking and active pursuit (see Parsons et al. (2006a,b) and Scarpaci et al. (2008, 2009, in press) for reviews of re-