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# Influences of the underwater man-made noise on acoustic behavior of dolphins

Fumio Nakahara

*Otsuchi Marine Research Center, Ocean Research Institute, The University of Tokyo,*
*Akahama, Otsuchi, Iwate 028–1102, Japan*
*E-mail: nakahara@wakame.ori.u-tokyo.ac.jp*

Human activities at the ocean, such as commercial transportations, industrial constructions and recreational activities, have expanded over the last century, both in coastal and offshore waters. This review summarizes the literature on underwater noise pollution, focusing on the effects of man-made noise on acoustic behavior of dolphins. The noise masks auditory systems of dolphins and reduces the range of echolocation and communication, that could have significant deleterious effects on the populations. One strategy of dolphins to alleviate masking is to shift the frequency of the signal away from the background noise and to increase the intensity of signals. Effects of man-made noise on the acoustic behavior of dolphins are little known. Modifications in the acoustic behavior have been reported in a few species, but the observed reactions are various both within and between studies. It is evident that more research on the noise pollution is necessary.

**Keywords:** dolphins, underwater noise, noise pollution, masking, acoustic behavior

## INTRODUCTION

In recent years, concerns about the impacts of human activities and the effects of environmental degradation on marine mammals have been greatly increasing. 'Noise pollution' is one of the great issues because the marine mammals depend highly on acoustic sensory abilities.

There are a great variety of sound sources in the oceans and the noises from all of them propagate well in the sea. Sources of noises in the oceans include the natural ambient and the man-made noises. The ambient noise arises from winds, waves, surfs, ice blocks, organisms, earthquakes, volcanoes, and more (Wenz 1962). Most man-made noises that could affect marine mammals arise from a few general types of activities in and near the sea; transportation, dredging, construction, hydrocarbon and mineral exploration and recovery, geophysical surveys, sonars, explosions, and ocean science studies (Richardson and Würsig 1997). Broadband source levels of underwater man-made noises are highly variable between noise sources: 152 dB re 1 $\mu$Pa@1m for Zodiac to 279 dB for TNT bomb (Malme et al. 1989).

Cetaceans are potentially particularly vulnerable to acoustic disturbance, because of their acute hearing ability and heavy dependence on acoustics. It is possible that increased levels of the underwater noises could be affecting cetaceans in a number of ways such as interfering with their ability to detect biologically important sounds, disturbing their behavior and impairing their hearing sensitivity (Gordon and Moscrop 1996). While there are many reports on the noise effects on larger cetaceans, especially for baleen whales (reviewed in Richardson et al. 1995, Gordon and Moscrop 1996, Richardson and Würsig 1997), the noise effects on the dolphins have been much less studied.

The dolphins produce a wide variety of complex vocalizations which have been categorized into pulsed and narrow-band frequency-modulated whistles (Evans 1987, Richardson et al. 1995, Akamatsu 1997). Pulsed signals including broad-band clicks used for the echolocation (Norris 1969) and burst-pulsed signals which are emotive and vocative in nature (Caldwell and Caldwell 1967). Clicks are generally at high frequencies, extended to the ultrasonic range, up to 150 kHz (Au 1993). Whistles have generally lower frequenies than clicks, mostly below 20 kHz. It has been hypothesized that individual dolphin produces a stereotypical whistle, which is supposed to have a role of the individual and the conspecific recognition and the contact call to maintain physical or vocal contact (Tyack 1986, Caldwell et al. 1990, Nakahara 1998, Tyack 1998). Source levels of these sounds are highly variable: $\leq$150 to 228 dB re 1 $\mu$Pa@1m for clicks and $\leq$80 to $\geq$180 dB for whistles (Richardson and Würsig 1997). Various dolphin species produce pulsed sounds, whistles, or both (Evans 1987, Richardson et al. 1995. Akamatsu 1997).

Auditory sensitivity of dolphins are most sensitive at 10–80 kHz (Fig. 1) adapted to their vocal frequency range. Though the low-frequency hearing ability has not been studied in many species, at least the bottlenose dolphin (*Tursiops truncatus*), beluga (*Delphinapterus leucas*) and Pacific white-sided dolphin (*Lagenorhynchus obliquidens*) are reported to hear sounds as low as 100 Hz (Johnson 1967, Awbrey et al. 1988, Tremel et al. 1998). Below 1 kHz, where the most man-made noise energy is concentrated, the sensitivity appears to be poor. However, broadband noises of vessels, sonars and sounds used for seismic survey have certain components at the high frequency range, which is thought to mask the dolphin auditory systems.

Most of the studies addressing the problem of the effects of noise on dolphins have used behavioral attributes such as the changes in site fidelity, dive patterns, swimming speed, orientation of travel and herd cohesiveness (Au and Perryman 1982, Acevedo 1991, Bowles et al. 1994, Janik 1996, Goold 1996, Würsig et al. 1998). In this paper, I review the influences of underwater man-made noise on acoustic behavior of dolphins.

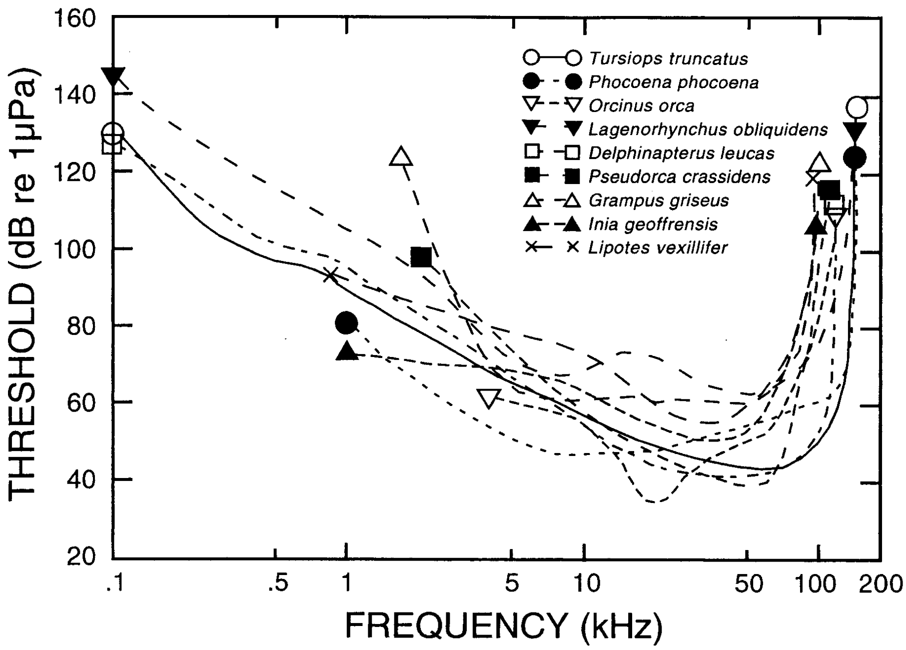


**Fig. 1.** Underwater audiograms of dolphins: beluga, *Delphinapterus leucas* (White et al. 1978, Awbrey et al. 1988); bottlenose dolphin, *Tursiops truncatus* (Johnson 1967, Ljungblad et al. 1982); killer whale, *Orcinus orca* (Hall and Johnson 1972, Bain et al. 1993); false killer whale, *Pseudorca crassidens* (Thomas et al. 1988); Risso's dolphin, *Grampus griseus* (Nachtigall et al. 1995); Pacific white-sided dolphin, *Lagenorhynchus obliquidens* (Tremel et al. 1998); harbor porpoise, *Phocoena phocoena* (Andersen 1970); boutu, *Inia geoffrensis* (Jacobs and Hall 1972); baiji, *Lipotes vexillifer* (Wang et al. 1992). Graph shows the animal's absolute auditory threshold versus frequency.

## MASKING EFFECTS ON AUDITORY CAPABILITIES

Noise reduces dolphin's ability to detect other sounds of similar frequency. In these animals, the ability to recognize sound signals amidst noise is important in communicating, detecting predators and locating preys. The range at which an animal can communicate or echolocate will be reduced by the noises of masking frequencies.

The echolocation capabilities of dolphins can be seriously affected by noise (Au and Nachtigall 1993). Experiments with echolocating bottlenose dolphins have shown that their target detection and discrimination capabilities can be severely degraded by the introduction of masking noises. In most situations, the dolphin compensated for the presence of masking noise by emitting more clicks per scan and by increasing their signal intensity (Au and Nachtigall 1993).

Reduction in the effective range of communication due to the masking could have significant deleterious effects of populations. For example, if calls used to recruit other animals to cooperative feeding bouts were disrupted, the overall feeding rate for the population would be reduced. If contact calls designed to maintain group cohesion were masked, the social organization could be disrupted. Separation of dependent youngs from their mothers is a potentially severe consequence of the disturbance-induced social disruption (Richardson et al. 1995).

Little is known about masked hearing abilities of dolphins. The signal-to-noise (S/N) ratio required to detect a pure-tone sound signal in the presence of background noise is called the critical ratio (Richardson et al. 1995). A low critical ratio suggests a good ability to detect low amplitude signals in a noisy environment. Critical ratios tend to increase with increasing frequency, except at quite low frequency (Fig. 2). In a bottlenose dolphin, a pure-tone signal at 6 kHz had to exceed the spectrum level noise by 22 dB to be detected, whereas a 70 kHz tone had to exceed the spectrum level noise by 40 dB (Johnson 1968). On the other hand, Lemonds et al. (1997) described that the critical ratios averaged over the noise levels were constant between 40 and 120 kHz, averaging 26 dB. For beluga, critical ratios were found to be about 3 dB lower than those of the bottlenose dolphin (Johnson et al. 1989). At lower frequencies, the critical ratio for the false killer whale (*Pseudorca crassidens*) decreased with frequency at a much higher rate than for the beluga and the bottlenose dolphin (Thomas et al. 1990).

Most masking studies present the signal and the masking noises from the same direction. The sound localization abilities of dolphins suggested that if the signal and the noise come from different directions, the masking would not be so severe as critical ratio data suggest (Richardson et al. 1995). Directional hearing may significantly reduce the masking effects of the noise by improving S/N ratio. In the case of high-frequency hearing by the bottlenose dolphin, beluga, and killer whale (*Orcinus orca*), the empirical evidence confirms that the masking depends strongly on relative directions of arrival of sound signals and the masking noise (Au and Moore 1984, Penner et al. 1986, Bain and Dahlheim 1994).

## ZONE OF MASKING

In assessing the potential effects of man-made noise on the dolphin acoustic behavior, it is important to estimate the radius around a noise source within which acoustic effects are expected. The zone of masking is the region within which the noise is strong enough to interfere with the detec-

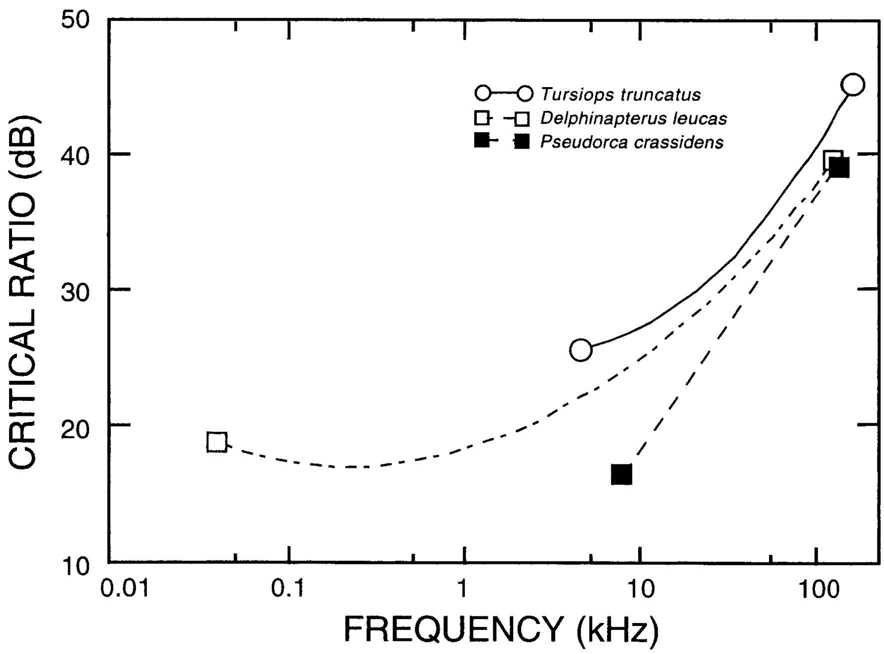


**Fig. 2.** Critical ratios of dolphins: beluga (Johnson et al. 1989); bottlenose dolphin (Johnson 1968, Au and Moore 1990); false killer whale (Thomas et al, 1990). Critical ratio is the difference between the sound level for a barely audible tone and the spectrum level of the background noise at nearby frequencies.

tion of other sounds, such as communication or echolocation signals, prey sounds, or other natural environmental sounds (Richardson et al. 1995).

The significance of auditory masking to dolphins is difficult to assess, given the uncertainties about the importance of various types of dolphin vocalizations and other natural sounds to dolphins. The area where the masking will occur is highly variable and the size of masking zone depends on the many factors. The radius of masking is affected not only by the received levels of man-made and ambient noises, but also by the level of the sound signals of interest.

Nakahara (unpub. data) estimated the potential masking range of bottlenose dolphin whistles (10 kHz) using a sound-propagation equation (see Richardson et al. 1995, Johnston and Woodley 1998) based on critical ratio of the dolphin (25 dB at 10 kHz) and a theoretical model sound-propagation condition. The severity of masking depends on the source level of the dolphin whistle. When the listening dolphin is closer to the whistling animal, a faint whistle (e.g., 125 dB re 1 $\mu$Pa@1m) could be masked even by a distant source of the man-made noise (e.g., a 200-dB sonar 25 km away and a 160-dB tanker 1.5 km away), while a loud whistle (e.g., 170 dB) would be masked only if the animal is considerably close to the source of noise (e.g., a 200-dB sonar 1 km away and a 160-dB tanker 7 m away).

Besides the dependence on signal source level and on relative distances of the receiving dolphin from the signal and noise sources, there are many reasons why no single radius of the masking can be defined. Factors affecting the radius of masking will also include the transmission loss from each source listener, directional hearing abilities, relative directions from listener to sources of the signal and the masker, and whether a signal level or frequencies are adjusted in response to the masking sound (Richardson et al. 1995).

## SIGNAL ADAPTATIONS TO REDUCE MASKING

One strategy to alleviate the masking is to shift the frequency of the signal away from the background noise and to increase the intensity of signals. The shift in frequencies may be an attempt to increase signal detectability by avoiding frequencies where the masking is more severe.

Some dolphins can adapt their echolocation signals appropriately to alleviate the effects of noise (Au et al. 1974, 1985, Moore and Pawloski 1990, Thomas and Turl 1990, Romanenko and Kitain 1992). Au et al. (1985) observed that the belugas shifted their click trains toward frequencies with less ambient noise when in the noisiest environment. Although the use of high-frequency click trains is definitely related to the high ambient noise environment, it is also acknowledged that high-frequencies may be an inevitable by-product of producing a high intensity signal (Au et al. 1985, Au 1993). Avoidance of the noisiest frequency band during echolocation has also been reported in bottlenose dolphins (Au et al. 1974) and false killer whales (Thomas and Turl 1990). Dolphins may change their echolocation spectra particularly when conditions of echolocation are very severe (Romanenko and Kitain 1992).

Adaptation of the communication signals is only observed in belugas. Lesage et al. (1999) reported a shift in frequency bands of beluga's calls when vessels were close to them. The belugas used high frequencies when exposed to the ferry and the outboard motorboat.

These examples indicate that some dolphins can at least adapt their vocalizations appropriately to alleviate the effects of background noise. However, it also shows that the masking may be serious enough to trigger a substantial change in vocalization. If we accept that the vocalization produced in the less acoustically constrained environment is of the most efficient type, then it must follows that the animal's vocalization in the noisy environment, although optimized for the environment, would be in some way less effective than in the less acoustically constrained environment. It is assumed to have some negative impact on dolphin communication and echolocation when the man-made noise is introduced into an environment.

## ACOUSTIC BEHAVIORAL RESPONSES TO NOISE

Modifications in the acoustic behavior when dolphins are exposed to the noise have been reported for a few species. A common reaction of larger cetaceans to the noise is to cease or reduce vocalizing (Watkins and Schevill 1975, Watkins 1986, Richardson et al. 1990, 1995), but reactions of dolphins are various both within and between the studies.

There are some reports of vocal responses to the disturbance from long-finned pilot whales (*Globicephala melas*). Bowles et al. (1994) observed a reduction in pilot whale sightings and a complete cessation of calling during broadcasts of low-frequency sounds from a distant seismic ship. While Rendell and Gordon (1999) reported a tendency for pilot whales to respond vocally to military sonar pulses.

Belugas exposed to a large ship and an icebreaker remained vocal and emitted a large proportion of falling tonal and noisy pulsive calls, while narwhales (*Monodon monoceros*) became silent when exposed to the same noise source (Finley et al. 1990). Lesage et al. (1999) also monitored the vocal behavior of belugas before, during and after exposure to the noise from vessels, and reported that the overall calling rate reduced while vessels were approaching, but the emission of falling tonal calls and pulsed-tone calls increased briefly, and the repetition of specific call increased at the distances $<1$ km from vessels. Finley et al. (1990) hypothesized that pulsed tones and falling tonal calls were alarm calls, as they were heard from belugas almost exclusively during the ship and the icebreaker exposed periods.

These studies have shown that pilot whales and belugas modify their acoustic behaviors when the background noise levels changes temporary. Call types, calling rates and frequency of calls may change possibly to improve the call detectability. However, as many vocalizations have communication functions, these changes probably reduce the communication efficiency and could cause some social disruptions.

## CONCLUSIONS AND PROSPECTS

Effects of noise on the acoustic behavior of dolphins, especially free-ranging dolphins, are not well known. Almost all the available data concerned with the masking effects are limited to laboratory studies. Adequate quantification of the dolphin's vocal response to noise is mostly hampered by technical limitations, mainly due to the difficulty of observing their underwater behavior and detecting their high-frequency underwater signals in the open water.

Modifications in the acoustic behavior have been reported in a few species, but reactions are variable both within and between studies. The variability in reactions could be due to a number of different physical and biological factors. The former includes the characteristics and the levels of the noise at dolphins, and the latter includes the hearing capability of the animals, their current activity, the threshold of disturbance, and the degree of habituation (Lesage et al. 1999).

To assess potential effects of the man-made noise, more data are needed on the significance of various sound signals to dolphins, and on the ranges over which they normally listen to these signals. Also the data on noise masking under field conditions, the compensatory mechanisms and the consequences of the interrupted acoustic communication are needed.

In Japan, to the problem of underwater noise pollution is not attached importance, compared with the organohalogen and the heavy metal contaminations. However, many sources of the man-made noise exist around Japan, and dolphins are exposed to these noises. It is considered that the impact of noise pollution on the dolphin communication and the echolocation is not negligible. Humans have to be more careful to avoid polluting the habitat of dolphins by noise as well as chemical contaminants.

It is evident that more research on the noise pollution is necessary. And we also have to study the normal acoustic behavior of dolphins to understand the noise effects. If the effects are well defined, it will become possible to regulate the noise exposure in the way that protects dolphins while minimizing the burden of human activities.

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# 水中人工雑音によるイルカ類の音響行動への影響

中原　史生

東京大学海洋研究所大槌臨海研究センター
〒028–1102　岩手県上閉伊郡大槌町赤浜2–106–1

近年，海洋における商業交通，産業建築やレクリエーションなどの人間活動は，沿岸においても沖合においても拡大しつつある．この総説では，人工雑音がイルカ類の音響行動に与える影響に焦点を当てて，水中騒音汚染に関する研究を紹介する．水中雑音は，イルカの聴覚機構をマスクするとともに，エコーロケーションやコミュニケーションの可能な範囲を減少させ，イルカの個体群に有害な影響を及ぼすものと考えられる．マスキングを避ける一つの戦略として，音声信号の周波数を背景雑音の周波数域から偏移させ，信号の強さを増加させるという手段がある．しかしながら，人工雑音がイルカ類の音響行動に与える影響はよくわかっていない．人工雑音による音響行動の変化は，幾つかの種において報告されているが，観察された反応はひとつの研究の中でも異なった研究の間においても変化に富むものであった．騒音汚染に関するさらなる研究が必要である．

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