Underwater bow-radiated noise characteristics of three types of ferries: implications for vessel-whale collisions in the Canary Islands, Spain

MICHAEL SCHEER[1] AND FABIAN RITTER[2]

(1) pilot-whales.org, Brunnenstr. 15-16, 28203 Bremen, Germany
(2) M.E.E.R. e.V., Bundesallee 123, 12161 Berlin, Germany

contact emails: mscheer@uni-bremen.de, ritter@m-e-e-r.de

ABSTRACT

Lethal collisions of vessels with whales are increasing worldwide. Often whales do not appear to move out of the path of approaching vessels to avoid a collision; the reasons for this are unclear. Until now, the underwater acoustics of ferries were also largely unknown. In the Canary Islands, a large number of stranded cetacean carcasses have shown injuries typically attributed to ship strikes. To further investigate the processes leading to vessel-whale collisions, the underwater bow-radiated noise of regular, fast, and high-speed ferries was recorded during passages off La Gomera in September 2012. Acoustic recordings and ferry tracking were carried out from a research vessel using a single calibrated hydrophone suspended to a depth of 15 m and Automatic Identification System (AIS) signals. Ferries were recorded in their forward-projected track at +/-3% maximum speeds from 4 km distance to the closest point of approach (CPA). For each ferry type, the passage with the nearest CPA was chosen for detailed analysis. Received levels (RLs) of ten frequency bands in the range of 0.5 – 90 kHz were spectrographically analysed and correlated with distances to the ferries. RLs of ambient noise were subtracted from the ferry noise RLs. By applying a critical ratio of 10 dB, results showed that the fast ferry was detectable at 1.67 km, the regular ferry at 1.61 km, and the high-speed ferry at 1.37 km. Given the speed of the ferries, a whale would potentially have 2.53 min, 3.5 min and 1.38 min, respectively, to swim out of the ship's path. While these time frames appear to be long enough to initiate an avoidance reaction, we believe that the high-speed ferry run under highest velocity, thus requiring the shortest reaction time presents the greatest risk for collisions with cetaceans.

INTRODUCTION

Lethal collisions of vessels with whales are increasing worldwide (Laist et al. 2001; Panigada et al. 2006; Van Waerebeek et al. 2007; Douglas et al. 2008; Carillo & Ritter 2010). The global growth in marine traffic and the increase in ship speeds both contribute to the increased probability of a collision (Laist et al. 2001; Vanderlaan & Taggart 2007, 2009; Wiley et al. 2011). Often whales do not appear to move out of the path of approaching vessels to avoid a collision. The reasons for this are unclear but it is possible that acoustic output from the ferries may be a factor. As shown by Nowacek et al. (2003), right whales did not respond to playback of ship noise but instead to alerting stimuli. Miller et al. (2008) reported that sperm whales did not react to an approaching vessel (with engines turned off) during drift-dives close to the water surface when they might be sleeping. Although sensory abilities, behavioural state, a lack in alertness, habituation or other factors can critically influence the detectability of the noise from approaching vessels, one might also assume that distinctive underwater acoustic cues, or their absence, play an important role in the whales' ability – or inability - to discriminate acoustic signatures of approaching vessels from background noise. From the animal's perspective its hearing thresholds are critical in the perception of distinctive sounds. Vessel noise is embedded in ambient noise and critical ratios (CRs) - defined as the difference between the level of a detectable tone and the spectrum level of background noise spanning the same frequency (Johnson 1968) - influence the detectability, localisation and identification of a sound. Thus, the sounds of approaching vessels are distinguishable from the background noise only when they are loud enough to exceed the masked thresholds (Gerstein 2002).

To investigate the processes leading to vessel-whale collisions, it has been proposed to study vessel noise characteristics at different distances, particularly in front of vessels and within the frequency range of marine mammal vocalizations (Laist et al. 2001; Hildebrand 2009). Acoustic signatures of several ship classes have been studied in open ocean environments (Arveson & Venditis 2000; Kipple & Gabriele 2007; Hatch et al. 2008; Allen et al. 2012; Bassett et al. 2012; McKenna et al. 2012). However, most of these studies focused on overall vessel noise budgets. In the Canary Islands, a large fleet of commercial ferries operates on a year-round basis (Ritter 2010). At the same time, a high number of stranded cetacean carcasses in the area have shown injuries typically attributed to ship strikes (Carrillo & Ritter 2010; Arbelo et al. 2013). Ferries regularly transit between the islands through important habitats of coastal and offshore species, some of which constitute resident populations (Heimlich-Boran 1993; Mayr & Ritter 2005). These vessels cross areas that have been designated as Special Areas of Conservation under the European Union Habitat Directive (Elejabeitia & Urquiola 2009; Ritter 2010). Until now, the underwater acoustics of the ferries and in particular underwater bow-radiated noise characteristics were largely unknown until now while the reasons for collisions remain unclear.

MATERIALS AND METHODS

Recordings of underwater sound characteristics of three types of ferries were made during September 2012 off the island of La Gomera (Canary Islands, Spain; Figure 1). The 10.6 m sailing vessel *Kalimba* with an auxiliary diesel engine was used as a mobile recording platform. Recordings were made during ferry passages after the recording vessel was positioned in the projected track of an approaching ferry. Recordings were made using a pre-amplified (± 20dB) and calibrated C55 hydrophone (mean sensitivity -163.8 dB re 1V/µPa; frequency response 0.009-100 kHz +3/-12 dB) manufactured by Cetacean Research Technology (USA) and a Tascam HD-P2 portable compact flash recorder (TEAC cooperation, USA) with a built-in anti-aliasing filter operating with a sample rate of 192,000/s at 24 bit. The frequency response of the recording system was 0.009-96 kHz (+3/-12 dB). In order to minimize flow-noise disturbance, the hydrophone was attached to a self-made flexible mounting which reduced the effects of vertical movements of the recording vessel. During recordings, the hydrophone was suspended to a depth of 15 m and the engine of the recording vessel was turned off. One reference recording was made at a depth of 3 m below the surface. The position of the recording platform at the beginning and at the end of each recording session was measured using a GPS Navigator. Water depth was subsequently retrieved from a Spanish sea chart (SP 517, Instituto Hidrografico, Cadiz). Information on ferries such as name, ship identification, distance to the recording vessel and ferry speed were obtained from an AIS100 automatic identification system receiver (Digital Yacht, UK), visualized by INaVX software (V1.0.2. Navionics, Italy) on an iPad tablet computer.

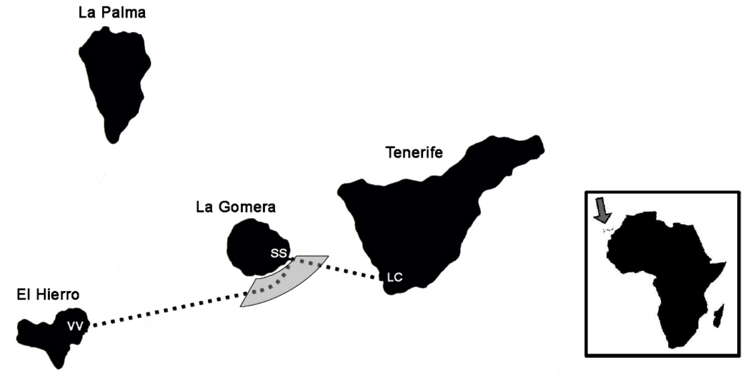


***Figure 1**. Map of inter-island ferry transects (dashed lines) with the harbours of Valverde (VV), San Sebastian (SS) and Los Cristianos (LC) in the Canary Islands, northwest Africa (inner map). The gray shaded area southwest off La Gomera shows field site where recordings were obtained.*

Ferry name	Ferry type	MMSI number	Length	Draft	Gross tonnage	Horse power	Capacity	Propulsion type	Max. speed
Benchijigua Express	Trimaran high-speed ferry	224441000	126 m	4 m	8.973 t	49.490 HP	1.350 passengers 337 cars	jet	40.5 kn
Volcan de Taburiente	Monohull fast ferry	224277000	132 m	5.7 m	15.000 t	24.000 HP	1.500 passengers 300 cars	2 x screw propeller	22.6 kn
Volcan de Tauce	Monohull regular ferry	224761000	120 m	5.3 m	9.807 t	9.248 HP	450 passengers 96 cars	2 x screw propeller	15.4 kn

***Table 1**. Summary of technical ferry characteristics being recorded during this study.*

Three different ferry types characterized by propulsion type and cruising speed (see Ritter 2010) were recorded: (a) regular ferry (*Volcan de Tauce*), (b) fast ferry (*Volcan de Taburiente*) and (c) high-speed ferry (*Benchijigua Express*, see Table 1 for ferry specifications). Ferries arrived at or departed from the harbours of Los Cristianos (Tenerife), San Sebastian (La Gomera) and Valverde (El Hierro, see Figure 1). Before each vessel passage, ambient noise level was recorded for 4 minutes. Received Levels (RLs) of ambient noise samples were measured using spectral analysis of the first 20 sec slices of each successive minute. Ambient noise was only recorded when any AIS transmitting vessel was at least 10 km distant from the recording vessel and no other vessels were in sight or appeared during recordings. All ambient noise recordings were made between 11 and 12 p.m. and in deep waters (500-1,000 m). Ferry passages were sampled every 10 s as soon as the vessel was within 4.0 km of the recording vessel. Sounds recorded during this approach until the closest point of approach (CPA) was defined as the forward directed bow beam. Only passages where ferries travelled at or close to (<3%) maximum speed were used for analysis, i.e. acceleration and deceleration phases during harbour departures and arrivals were not considered. Recordings were analysed using Raven Pro 1.4 software (Cornell Lab of Ornithology, Bioacoustics Research Program). Spectral analysis (512 FFT, 50% overlap) of received noise levels (RLs) for frequency bands at 0.5, 1, 5, 10, 15, 20, 25, 30, 50 and 90 kHz were made from 5 s slices taken from each successive 10 s sample for the complete sampling interval. To calculate RLs of ferry noise above background noise (=critical ratio exceedance; CRE), RL of ambient noise was subtracted from the corresponding RL of frequency bands attributed to ferry noise. The identical background noise level (recorded on 18.09.12 at 11:50:00 p.m.; 650 m) was applied to all measured approaches (*Volcan de Taburiente*: 17.09.12 at 11:29:00 p.m.; 1,000m / *Benchijigua Express*: 18.09.12 at 11:59:00 p.m.; 580 m and *Volcan de Tauce*: 14:47:00 p.m.; 650 m) so as to make RLs above background noise comparable.

RESULTS

During eight days at sea 18 ferry recordings were made. For each ferry type the passage with the nearest CPA was chosen for analysis (see Table 2). During six recordings, the vessel could be positioned in the projected track of the ferries but CPAs still were comparably far away (*Benchijigua Express*: 1.7-2.78 km, n=4; *Volcan de Taburiente*: 3.17-3.22 km, n=2). For the regular ferry *Volcan de Tauce* only a single recording was obtained which was then used for analysis. Nearest CPAs were 0.33 km for the fast ferry, 0.41 km for the regular ferry and 0.96 km for the high-speed ferry.

RLs of ambient noise measured in advance of each ferry approach are shown in Figure 2. RLs of ambient noise can vary. For the measurements at 15m depth the ambient noise level measured on 18.09. exceeded the level measured on 17.09. by a mean of 12.1 dB (S.D. ±3.9). The measurement at 3 m depth showed that RLs were even higher (mean: 15.6 dB, S.D. ±6.1).

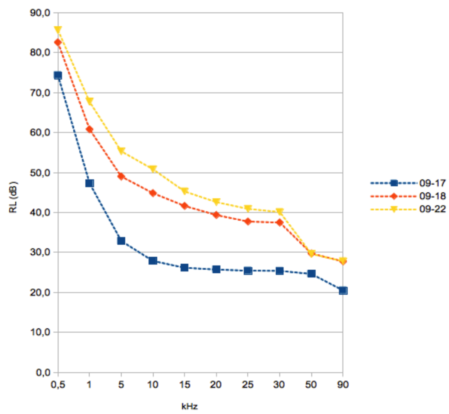


Figure 2. *Measurements of absolute RLs (dB) for selected frequency bands from 0.5 to 90 kHz on 17.09.12 (time of day: 11:10:00 p.m.; water depth: 1,000 m), 18.09. (11:50:00 p.m.; 650 m) and 22.09. (11:50:00 p.m.; 500 m; hydrophone suspended to 3 m).*

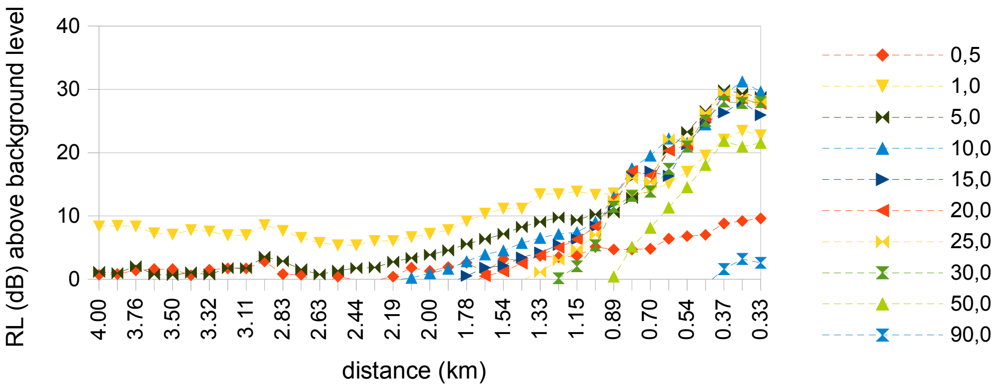
Figure 3 shows RLs above background level for the ten selected frequency bands for each ferry type. Figure 4 compares absolute RLs of the peak frequencies 1, 5 and 10 kHz among ferry types between 4 km distance and CPAs. It can be stated that the closer a ferry approaches, the more its noise exceeds the background noise level. However, because CPAs differed between ferry types, a consistent comparison for distances of less than 0.96 km was not possible. Table 2 summarizes distances at CRE, peak frequencies at CRE and remaining time from CRE to potential collision (i.e. when the ferry would reach the location of the whale) for CRs 10-30 dB, as well as absolute RL values of peak frequencies at CREs. Depending on ferry type and distances, these values ranged 71.2-72.6 dB for the 1 kHz band, 59.1-75.6 dB for 5 kHz and 62.4-76.1 dB for 10 kHz. Peak frequencies at CRE (CR=10 dB) differed between the propeller-driven ferries (1 kHz) and the jet-driven high-speed ferry (5 kHz). Applying higher CRs led to smaller distances at CRE, as long as it could be shown that CRs were exceeded. By applying a CR of 10 dB, the fast ferry was detectable at a distance of 1.67 km which results in a remaining time of 2.53 min to a potential collision from the distance at CRE. The regular ferry could be detected at a distance of 1.61 km (remaining time: 3.50 min) and the high-speed ferry at a distance of 1.37 km (remaining time: 1.30 min). When applying a CR of 15 dB, remaining time decreased to 1.26 min for the fast ferry (peak frequency at CRE: 10 kHz; distance: 0.83 km) and 1.28 min for the regular ferry (peak frequency at CRE: 5 kHz; distance: 0.59 km). This CR (and all others above it) was not exceeded by the high-speed ferry until it reached CPA. All CREs with CRs of 15-30 dB for the fast and regular ferries occurred below the CPA of the high-speed ferry. At a CR of 30 dB the fast ferry had a remaining time of 0.53 min (peak frequency at CRE: 10 kHz; distance: 0.35 km) whereas both the regular and high-speed ferries did not exceed this CR (see Table 2).

Date	Time of day	Ferry name	Passage (from-to)	Ferry speed	Water depth at recording location	Distance at CPA[1]	Distance at CRE[2]	Peak frequency at CRE	RL of peak frequency at CRE	Remaining time from CRE to potential collision
17.09.12	11:29:00	*Volcan de Taburiente*	SS-LC	21.4 kts	1.000 m	0.35 km	10 dB: 1.67 km	1 kHz	71.2 dB	2.53 min
							15 dB: 0.83 km	10 kHz	62.4 dB	1.26 min
							20 dB: 0.59 km	10 kHz	67.1 dB	0.89 min
							25 dB: 0.44 km	5 kHz	75.6 dB	0.66 min
							30 dB: 0.35 km	10 kHz	76.1 dB	0.53 min
18.09.12	11:59:00	*Benchijigua Express*	SS-LC	32.2 kts	580 m	0.96 km	10 dB: 1.37 km	5 kHz	59.1 dB	1.30 min
18.09.12	14:47:00	*Volcan de Tauce*	LC-SS	14.9 kts	650 m	0.41 km	10 dB: 1.61 km	1 kHz	72.6 dB	3.50 min
							15 dB: 0.59 km	5 kHz	64.7 dB	1.28 min
							20 dB: 0.41 km	5 kHz	69.6 dB	0.89 min

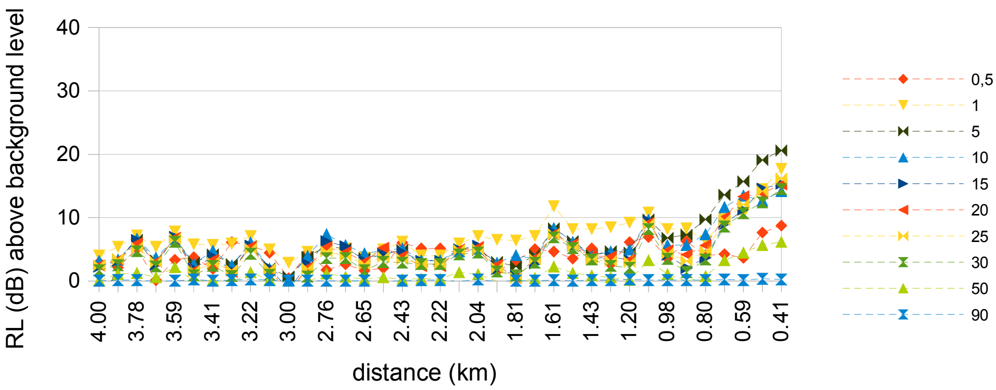
[1]Closest point of approach
[2]Critical ratio exceedance

Table 2. *Overview of selected ferry recordings and measurements during passages (SS = San Sebastian, LC = Los Cristianos) between the islands of Tenerife and La Gomera, Canary Islands. Ferries were each recorded from a 4 km distance to the closest point of approach. For all calculations, the same ambient noise level recorded on 18.09.12 was applied.*

(a) *Volcan de Taburiente*



(b) *Volcan de Tauce*



(c) *Benchijigua Express*

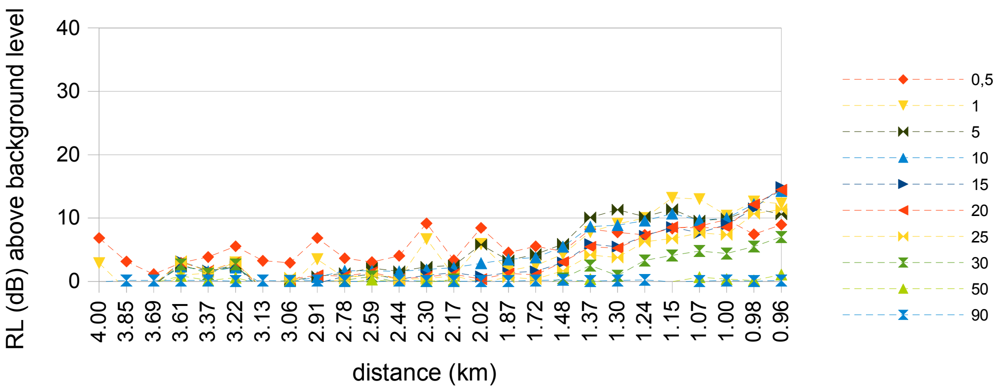


Figure 3: *RL (in dB) measurements above background level for selected frequency bands (0.5-90 kHz) during approaches from a 4 km distance to CPA for the (a) fast ferry, (b) regular ferry and (c) high-speed ferry with the hydrophone suspended to 15 m.*

a) 1 kHz

b) 5 kHz

c) 10 kHz

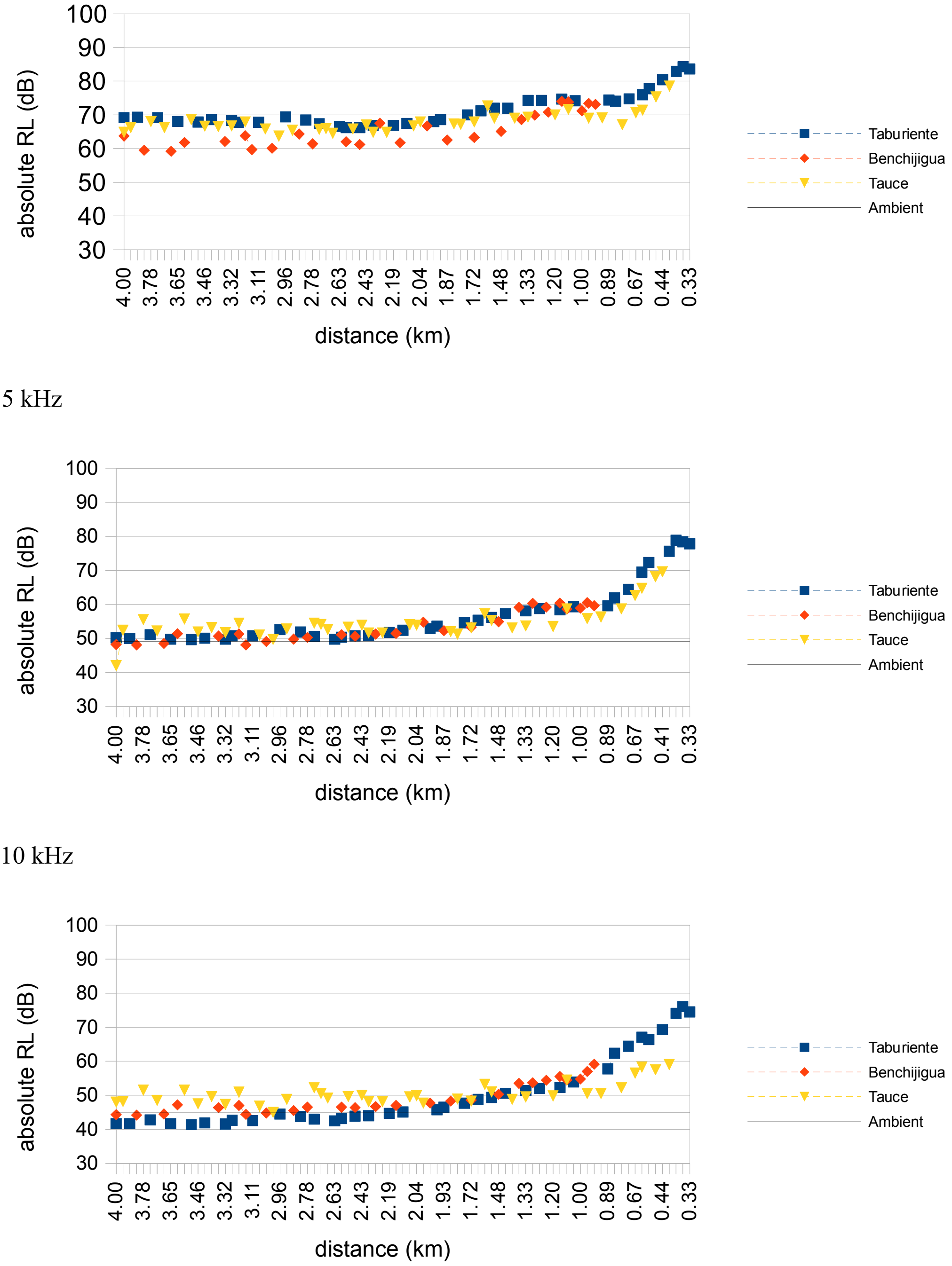


Figure 4: *Comparison of absolute RL (in dB) measurements for a) 1 kHz, b) 5 kHz and c) 10 kHz between ferry types during approaches from a 4 km distance to CPAs.*

DISCUSSION

Underwater bow-radiated ferry noise was recorded close to the water surface from a mobile research vessel. In combination with real-time AIS data, this method allowed measurements of vessel noise characteristics under non-experimental field conditions. However, some limitations have to be recognized. Although ferries used discrete shipping lanes, they did not use exactly the same routes during each transect making it difficult to position the boat into the projected track so as to enable us to record close approaches. In accordance with transportation regulations, ferries have to avoid close passages to other vessels for safety reasons. Researchers recently succeeded in synchronising speed, course and distance with vessel operators to optimize measurements (Gerstein 2002; Kipple & Gabriele 2007), but this was not attempted during this study. A direct synchronisation with larger ships in open ocean environments is hard to achieve for economical, safety and technical reasons.

For specific shipping lanes and locations, other studies used recordings from fixed bottom-mounted hydrophones, concentrating their measurements mostly on frequency bands lower than 2.5 kHz (see also Arveson & Venditis 2000; Kipple & Gabriele 2007 and Bassett et al. 2012). Those studies did not focus on the measurements of vessels approaching whales near the surface and hence did not take into account that cetaceans can also detect frequencies >2.5 kHz. While we achieved CPAs of less than 1 km for a limited number of passages during this study, the smallest distances were significantly closer than previous measurements obtained with fixed installations (1.2-3.0 km: Bassett et al. 2012; 2.6-3.5 km: McKenna et al. 2012). However, a comparison of acoustic signatures for distances below 0.96 km was constrained by the CPA given for the high-speed ferry.

As we are presenting single measurements in this paper, our results need to be treated with caution. CRs are essential for a whale to discern distinct sounds from broadband noise and to initiate an avoidance reaction, and ambient noise intensity is one determining factor. Despite the fact that recordings at 15 m depth were obtained at the same time of day and in deep waters, ambient noise levels were shown to vary substantially between days. This variation will affect the signal-to-noise ratio of ferry noise above background level and hence the remaining time to initiate an avoidance reaction. Surface swell can raise the ambient noise level up to 10 dB (Knudsen et al. 1948) although this also will decrease with increasing distance from the surface. The measurement with the hydrophone suspended to a depth of 3 m showed highest RLs which might be explained in this way. As pointed out by Richardson et al. (1995), ambient noise levels for a given frequency can vary by 10-20 dB from day to day, and even within minutes or seconds, thus limiting our ability to make assumptions about the subjective perception of additional noise sources. This is even more relevant for animals lying at the water surface where an increased level of ocean surface noise and acoustic shadow zones may come into play (Allen et al. 2012; for reviews see Richardson et al. 1995; Hildebrand 2009).

Each ferry type showed a unique frequency- and distance-specific energy content signature. These acoustic signatures might enable their (individual) recognition by the animals. It has also been shown for several ship classes and propeller types that noise intensity varies with speed (Richardson et al. 1995; Erbe 2002; Kipple & Gabriele 2007). However, Allen et al. (2012) showed that length to draft ratios rather than speeds of vessels could be positively correlated with increasing source levels of emitted noise. Because ferry speed can vary between passages we only used passages where ferries travelled at or close to (<3%) maximum speeds to exclude this aspect from analysis.

In this study, the interval of time between perceiving a ferry and until a potential collision was calculated to range from 0.53 to 3.5 min depending on ferry type and CR value. In the Canary Islands, sperm whales (*Physeter macrocephalus*), pygmy sperm whales (*Kogia breviceps*), Cuvier's beaked whales (*Ziphius cavirostris*) and short-finned pilot whales (*Globicephala macrorhynchus*) belong to the species most affected by ship strikes (Carrillo & Ritter 2010). Compared to their swimming speeds (Mörzer Bruyns 1971; Watkins et al. 1993; Miller et al. 2004; Tyack et al. 2006; Aguilar et al. 2008; Wells et al. 2013), these time frames appear to be long enough for an avoidance reaction for each of those species. Why then, do sperm and other whales often not avoid ferries quickly enough?

In cetaceans, CRs have only been examined for bottlenose dolphins (*Tursiops truncatus*), belugas (*Delphinapterus leucas*), false killer whales (*Pseudorca crassidens*) and harbour porpoises (*Phocoena phocoena*) (Johnson 1968; Johnson et al. 1989; Thomas et al. 1990; Kastelein et al. 2009). For these species, CRs for frequency bands below 20 kHz were reported to range between 15 and 30 dB. Therefore, applying the 10 dB CR for this study is a conservative assumption and hence, calculated time frames have to be seen as maximum values. Increasing CR from 10 dB to 20 dB has a dramatic effect on the results. As an example, remaining time from CRE to potential collision is reduced for the fast ferry by 65% and for the regular ferry by 75% (see Table 2). However, because CRs are not available for any of the affected species, it remains unknown at which distances their auditory sensitivity enables them to acoustically detect a ferry. Extrapolating this to the high-speed ferry, while taking into account that its RL of the peak frequency was lowest, we would expect a strongly diminished detectability and a substantial reduction of the available reaction time, thus increasing collision risk dramatically. However, this must remain speculative due to the lack of corresponding measurements. In any case, we were able to acoustically detect all three ferry types on the headphones at ranges of more than 4 km. As simple tones are used during critical ratio measurements, it should be taken into account that the interplay of several frequencies might be essential in detecting ferries from a distance.

Some studies show that cetaceans react to anthropogenic noise by avoiding the sound source (Watkins et al. 1993 and André et al. 1997 for sperm whales; Aguilar de Soto et al. 2006 for Cuvier's beaked whales; Weir 2008a for short-finned pilot whales) whereas others found no reaction to comparable stimuli (Madsen & Møhl 2000 and Weir 2008b for sperm whales). Through this work we were able to show that the frequency bands of 1, 5 and 10 kHz are essential in detecting ferries at distance. In this study, the time remaining to a potential collision was calculated from CREs of these peak frequencies. But the detectability of a sound also depends on its absolute RL. Depending on ferry type and distance, absolute RLs ranged from 59.1 to 76.1 dB for peak frequencies. Again, it remains unclear whether the whales are able to detect those frequencies at these intensities. As reviewed by Richardson et al. (1995), high-frequency hearing abilities are very good in small to medium-sized odontocetes and frequency-dependent thresholds between 8-90 kHz can be as low as 30-55 dB. By measuring auditory brainstem responses from stranded sperm and pygmy sperm whales, Ridgway & Carder (2001) found best hearing sensitivity at 5-20 kHz for sperm and 90-150 kHz for pygmy sperm whales. For short-finned pilot whales, Schlundt et al. (2011) found best hearing sensitivity at 40 kHz with a threshold below 80 dB. For frequencies at or below 20 kHz auditory thresholds were above 100 dB. These results make us speculate that RLs of the peak frequencies at CREs measured during this study could be above the hearing thresholds of pygmy sperm and short-finned pilot whales but below the thresholds of sperm whales. However, there are not enough data to underpin this assumption.

It has to be stressed that wild whales sometimes have reduced hearing capabilities. André (1997) reported significant hearing damage in sperm whales hit by ferries in the Canary Islands in 1996. Elsewhere, stranded cetaceans including short-finned pilot whales showed reduced hearing capabilities or even had profound hearing loss (Mann et al. 2010; Schlundt et al. 2011). Hence, reduced hearing or even hearing loss could be quite frequent in free-ranging cetaceans. Such animals obviously would be much more vulnerable to collisions because they might rely only on visual detection of ships.

In addition, there are other factors which affect collision risk but which are less dependent on the acoustic abilities of the animals. Cetaceans might also be inexperienced or be otherwise distracted by certain behaviours such as resting, foraging, or socializing. These behaviours can be gender or age-class specific, and younger animals would be more vulnerable. We note that many of the animals hit in the Canary Islands were juveniles and calves, underlining this assumption. Finally, it must be emphasized that the three cetacean species representing the largest proportion of collision victims are all deep divers. Sperm, beaked and short-finned pilot whales can stay at great depths for prolonged periods of time to forage. They are known to subsequently stay close or at the surface apparently to restore oxygen reserves (Watkins et al. 1993; Tyack et al. 2006; Aguilar Soto et al. 2008; Miller et al. 2008; Wells et al. 2013). An animal returning to the surface after an exhausting dive may not even be able to concentrate on (listen out for) approaching vessels, as oxygen recovery is so important at that time and their attention is therefore elsewhere. Hence, there also might be physical limitations to react in a timely manner to an approaching vessel. A combination of the aforementioned factors can further elevate the risk of a collision occurring.

To summarize, we were able to show that whales may be capable of hearing approaching vessels at reasonable distances enabling them to react in time, however there are numerous factors to be considered in evaluating the actual collision risk. Keeping in mind that the perception of an approaching ferry is complicated by variable ambient noise levels, critical ratio values and absolute sound intensities, the calculated remaining time frames to a potential collision probably represent overestimations. Additionally, on the whales' side a variety of factors including individual condition, behavioural state, time since the last deep dive as well as age and experience are important factors to take into account. Considering that ferries conduct up to 17,000 transects between the islands every year (Ritter, 2010), there may well be (many) situations where whales cannot hear fast approaching vessels early enough to react to them. This is particularly true because it is not clear whether the (directional) localization of sounds can be determined at the assumed CRs because avoidance requires that the animal knows in which direction it must move to escape the sound source. We conclude that jet-driven ferries traveling at high speed, combined with the comparably low intensity of their bow-radiated noise, results in a high risk of collision for cetaceans. As a mitigation measure to avoid collisions in the future, it has been suggested that vessel speed reductions should be implemented as a precautionary measure, especially within known areas with high cetacean densities and designated marine protected areas (Carrillo & Ritter 2010; Ritter 2010). Our results confirm that vessel speed is a crucial factor in the interplay between ships and whales and hence reinforces the need to reduce vessel speed so as to minimize the risk for the animals, vessel crews and ferry passengers alike. Apart from the acoustic detectability of noise, the biggest remaining question is if whales are able to assess when and where to swim so as to avoid being hit. While this study can be regarded as a first step in examining the qualitative change of acoustic signatures of approaching ferries, more systematic data on ambient noise, ferry noise measurements at closer distances as well as audiograms and critical ratios of the affected species will be needed to further understand acoustic principles involved in vessel-whale collisions.

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