High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (*Phocoena phocoena*)

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Growing ship traffic worldwide has led to increased vessel noise with possible negative impacts on marine life. Most research has focused on low frequency components of ship noise, but for high-frequency specialists, such as the harbor porpoise (*Phocoena phocoena*), medium-to-high frequency noise components are likely more of a concern. To test for biologically relevant levels of medium-to-high frequency vessel noise, different types of Automatic Identification System located vessels were recorded using a broadband recording system in four heavily ship-trafficked marine habitats in Denmark. Vessel noise from a range of different ship types substantially elevated ambient noise levels across the entire recording band from 0.025 to 160 kHz at ranges between 60 and 1000 m. These ship noise levels are estimated to cause hearing range reduction of >20 dB (at 1 and 10 kHz) from ships passing at distances of 1190 m and >30 dB reduction (at 125 kHz) from ships at distances of 490 m or less. It is concluded that a diverse range of vessels produce substantial noise at high frequencies, where toothed whale hearing is most sensitive, and that vessel noise should be considered over a broad frequency range, when assessing noise effects on porpoises and other small toothed whales. © *2014 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4893908]

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I. INTRODUCTION

Anthropogenic impacts on the marine environment are increasing as the exploitation of marine resources intensifies. A rapid growth in worldwide ship traffic has taken place over the past decades and is expected to continue to rise (National Research Council, 2003; Hildebrand, 2009). With increased ship traffic follows an increase in vessel noise, which is considered the dominant anthropogenic noise source in the world's oceans at low frequencies (National Research Council, 2005). Consequently, in the Pacific, a 15 dB rise in low-frequency (<100 Hz) ambient noise over 50 yrs from 1950 to 2000 has been reported to be a result of almost a tripling in the number of ships along with higher average ship speeds (Andrew *et al*., 2002; McDonald *et al*., 2006). Low-frequency sounds propagate with little loss to absorption and are therefore potentially able to affect marine life over large ranges (Urick, 1983).

Cetaceans are of special concern, when assessing potential impacts of anthropogenic underwater noise, as they are critically dependent on sound to communicate, navigate, and in the case of toothed whales, to forage by echolocation. All marine mammals have been protected in U.S. waters since 1972 by the Marine Mammal Protection Act with aims to obtain a sustainable population by, for example, prohibition of harassment, which leads to behavioral disruptions (Roman *et al*., 2013). In European waters, marine mammals have been protected since 1992 through the Habitats Directive (92/43/EEC; European Commission, 1992), which includes prohibition of deliberate disturbance of these species. Furthermore, the European Union recently included anthropogenic underwater noise as an explicit form of pollution in the Marine Strategy Framework Directive (MSFD; European Commission, 2008), where descriptor 11 requires that "*introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment*". In particular the annual average received levels in the third-octave bands [root-mean-square (rms)] with center frequencies at 63 and 125 Hz are highlighted by the technical subgroup for noise as relevant proxies for general noise levels from shipping (Tasker *et al*., 2010), as these frequency bands dominate ship noise in deep water (Ross, 1976; National Research Council 2003). Accordingly, the European Commission currently considers these two low frequency bands as indicators for ambient noise pollution in marine habitats (European Commission, 2010).

However, different vessel types have different acoustic signatures (Ross, 1976; National Research Council 2003; McKenna *et al*., 2012) and it is unknown whether the two MSFD frequency bands also serve as reliable proxies for mid- and high-frequency noise emissions from different ship types. Higher ship speeds have been shown to increase mid-to-high frequency noise levels (Arveson and Vendittis, 2000; Aguilar

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Soto *et al.*, 2006; Jensen *et al.*, 2009) as a result of cavitation noise from the formation and collapse of vapor bubbles on fast-moving propeller blades (Ross, 1976; National Research Council, 2003). Nevertheless, because of the high absorption of high frequency sounds, often in combination with recording gear limitations, little attention has been paid to the levels of high frequency vessel noise in marine habitats, and how these components may affect cetaceans.

Baleen whales produce sounds in the low frequency range, down to 10 to 15 Hz for the largest species, and their hearing is believed to be the most sensitive at low frequencies including the MSFD frequency bands around 63 and 125 Hz. However, for small toothed whales which produce and hear sound at high frequencies, up to and beyond 100 kHz (Au, 2000), the third-octave bands around 63 and 125 Hz are well outside their most sensitive hearing range. This large variation in the auditory systems of cetaceans points to a need for determining sound level indicators fitted to different species or at least species categories with different hearing capabilities (Southall *et al.*, 2007). The harbor porpoise (*Phocoena phocoena*) echolocates around 110 to 150 kHz (Møhl and Andersen, 1973) and has its most sensitive hearing between 80 and 140 kHz, whereas hearing thresholds are high below 1 kHz (Kastelein *et al.*, 2002; Kastelein *et al.*, 2010). Consequently, vessel noise in the MSFD frequency bands is likely not even audible to porpoises unless the received noise levels are very high. Furthermore, shallow marine waters, where porpoises are common, act as steep high-pass filters (Forrest *et al.*, 1993), where low frequency sounds propagate poorly or not at all. This is expected to result in medium-to-high frequency sounds becoming more dominant, despite the presence of broadband sources such as ships (National Research Council, 2003). Thus small toothed whales, such as porpoises, which have a poor low frequency hearing, generally live in areas with some of the highest shipping densities in the world (Hildebrand, 2009); however, low frequency sounds might propagate poorly in these waters. If shipping noise is only generated at low frequencies, this means that this type of noise source may not be of concern for toothed whale species, such as harbor porpoises. On the other hand, if shipping noise contains undocumented high frequency components, this could have considerable effects on the behavior and acoustic umwelt of these small toothed whales in shallow water. These questions provide an impetus for investigating the levels of high frequency vessel noise that porpoises and other small toothed whales may be exposed to in shallow waters.

Here, we report broadband (0.025–160 kHz) vessel noise levels recorded from different vessel types in four heavily ship-trafficked marine areas in Denmark. We evaluate vessel noise levels in shallow water in light of the potential impacts on porpoises and other small toothed whales, and we discuss the limitations of the proposed 63 and 125 Hz third-octave bands indicated in the MSFD in relation to mitigation of effects on medium-to-high frequency species.

II. METHODS

A. Recording areas

The recordings were made in four shallow water (15–20 m) marine locations in Denmark with sandy bottom; two locations in Aarhus Bay (southern Kattegat) and two locations in the Great Belt (Fig. 1). All areas have a high shipping intensity [Fig. 1(b)] and are inhabited by harbor porpoises (Sveegaard *et al.*, 2011). Ship traffic in Aarhus Bay is dominated by passenger fast ferries operating between Aarhus and the island of Zealand up to 13 return trips a day, with almost all crossings in the time period from 6 a.m. to 9 p.m. corresponding to a ferry passing approximately every 40 min. The Great Belt serves as the deep water connection between the Baltic Sea and the North Sea, making this strait heavily trafficked at all times of the day by large ships, such as tankers and bulk carriers, but also smaller vessels of different types.

B. Acoustic recordings

Recordings of broadband vessel noise (0.025–160 kHz) were obtained from a small research vessel (R/V Tyra) by means of a TC4014 hydrophone (Reson, Slangerup, Denmark; sensitivity—186 dB 1 V/μPa; frequency range 0.01–160 kHz,

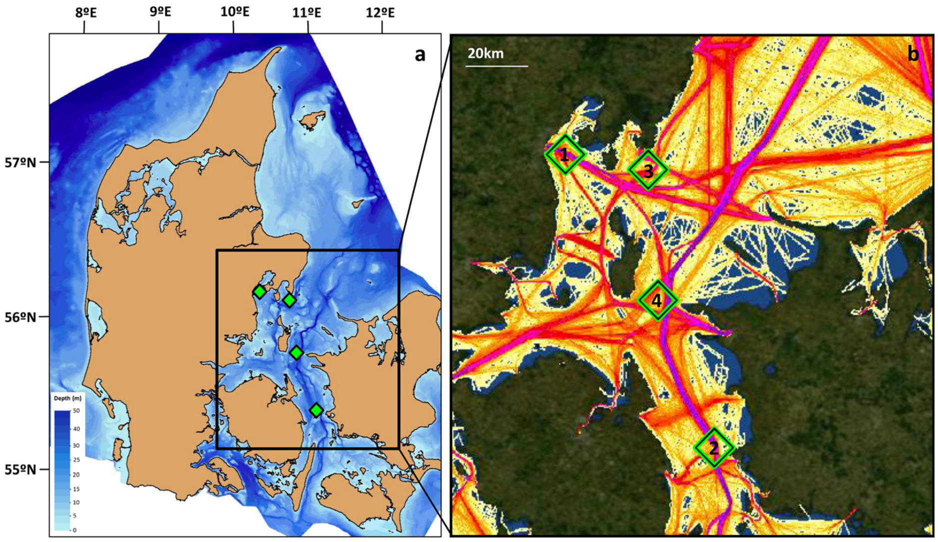

FIG. 1. (Color online) The geographic positions of the four recording areas (1–4; see Table I) in Denmark, marked with diamond shapes: (a) Map of Denmark and central parts of Danish waters with depth indications; data from sofart.dk. (b) Enlargement of the region of the four recording positions, showing the shipping intensity for July–August 2009 registered for ships with an onboard AIS (sofartsstyrelsen.dk). Darker areas indicate higher density of ships.

flat frequency response (± 2 dB)]. The hydrophone was at 7 m depth (approximately mid-water) and the hydrophone cable was mounted with five 15 cm trawl balls spaced 0.5 m apart at the surface, and 3 kg lead weights in the bottom to minimize vertical movements of the hydrophone caused by waves and swell. The hydrophone was connected through a low-noise amplifier (either A1001, ETEC, Frederiksværk, Denmark or a custom built amplifier; 20 or 40 dB gain, 1-pole, 10 Hz high-pass filter and 4-pole, 160 kHz low-pass filter) to a 16 bit AD-converter (National Instruments USB-6251 or USB-6356). Sounds were recorded on laptops running custom made software developed in LabVIEW (National Instruments, 2011 courtesy of Alain Moriat) with a sampling rate of 333 or 500 kHz and stored to disk in WAV format. The exact recording position and time were extracted from a custom-built Global Positioning System (GPS) receiver and continuously recorded on a separate channel in each wave file by means of a frequency shift keyed (FSK) signal (Møhl *et al.*, 2001). Continuous information about position and speed of nearby and passing vessels was obtained by logging Automatic Identification System (AIS) data from a portable AIS receiver (easyAIS S2C) by means of the ShipPlotter software (Centro de Observação Astronómica no Algarve), or obtained subsequently from the Danish Maritime Authority. The AIS time stamp was calibrated by synchronizing the AIS receiver and the recording computer, and by comparing calculated distances with distances noted directly during recordings from the integrated AIS onboard the research vessel.

To minimize noise interference, all engines, generators, and echo sounders on the research vessel were switched off during recordings. All recordings were obtained at sea state 2 or below. No change in sea state was registered during individual vessel noise or ambient noise recordings, thus no change in noise contribution from waves, wind, and rainfall was expected (Hildebrand, 2009). In recordings from the Great Belt in May 2012, frequencies above 12.5 kHz were excluded from analysis because of intermittent interference from an unidentified echo sounder or system noise, which could not be reliably removed. The recording chain was calibrated with a piston phone (Brüel & Kjær hydrophone calibrator type 4223) prior to each of the four recording days. The self-noise of the TC4014 hydrophone was measured in an anechoic chamber at the Danish Technical University with the same setup as used at sea.

Recordings were conducted on four days in 2012; March 14th and September 23rd in southern Kattegat, and May 9th and November 16th in the Great Belt. Recordings were initiated when an approaching vessel was 1.5 to 2.0 km away and ended when the vessel was approximately 1 km beyond the recording station. Ships were generally abeam at the time of closest point of approach (CPA), thus different ships were recorded under comparable noise radiation conditions. At times with no vessels nearby (>2 km to closest vessel) ambient noise recordings were made, as this was the closest to actual daytime ambient noise levels that could be obtained in these busy shipping areas. Ambient noise was recorded with a TC4032 hydrophone [Reson; sensitivity—170 dB 1 V/μPa, flat frequency response (±2.5 dB) from 10 Hz to 80 kHz] on March 14th, a TC4014 hydrophone on May 9th and a Brüel & Kjær 8101 hydrophone [sensitivity—184 dB 1 V/μPa, flat frequency response (±2 dB) from 1 Hz to 80 kHz] on September 23rd and November 16th. The

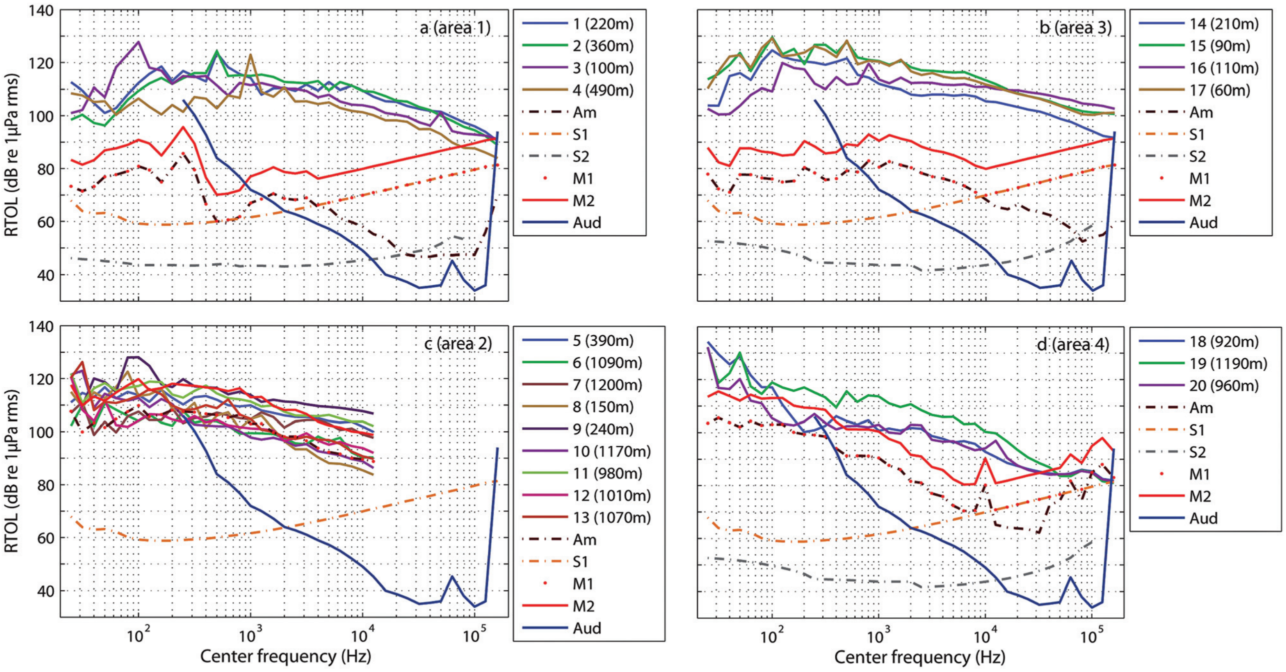

FIG. 2. RTOLs (dB re 1 μPa rms) of noise from 20 vessel recordings (1–20; Table I) recorded at varying distances (60–1200 m) on 4 recording days: (a) Aarhus Bay, Southern Kattegat, March 14th; (b) Southern Kattegat, September 23rd; (c) Great Belt, May 9th; (d) Great Belt, November 16th. Area numbers in brackets link to Fig. 1. Legend to additional plots: Am = ambient noise, $S1$ = self-noise of the TC4014 hydrophone, $S2$ = self-noise of the TC4032 or the B&K 8101, $M1$ = maximum of the ambient noise and self-noise levels, $M2 = M1 + 10$ dB, the criterion below which ship noise was not included in analysis, Aud = harbor porpoise audiogram after Kastelein *et al.*, 2010.

hydrophone used to record ambient noise was positioned just above (20 cm) or right next to the TC4014 hydrophone in mid-water. The nominal self-noise of the TC4032 hydrophone and the Brüel & Kjær 8101 hydrophone was obtained from Teledyne Reson Group and Brüel & Kjær (Master catalogue 1983), respectively (Fig. 2).

C. Broadband third-octave levels of vessel noise

Vessel noise recordings were quantified as received third-octave levels (RTOLs) at the time of CPA using a third-octave filter bank (*Filtbank*, provided by Christophe Couvreur, Faculte Polytechnique de Mons, Belgium) implemented in MATLAB (Mathworks, Inc., 2010R) according to the ANSI standard S1.6-1984 (1984). A third-octave level is the rms sound pressure in a one-third octave band, which approximates the effective filter bandwidth of the mammalian hearing system when detecting signals in broadband noise (Richardson, 1995; Madsen *et al.*, 2006).

The range between the recording station and the focal ship was calculated from the FSK-coded position of the recording station and the position of the passing ship obtained from AIS data. Analysis was performed only for recordings where no other ships were closer to the recording station than 2 km, to ensure recorded noise was in fact from the focal ship. Ranges to the nearest other vessel at the CPA are shown in Table I. RTOLs were computed over a time window of 3 s around the CPA, by evaluating with a moving window of 1 s (50% overlap). This window was chosen as a compromise between sufficient degrees of freedom at low frequencies (Green and Swets, 1966) and minimal change in the vessel's range and aspect over the analysis window. Ambient noise levels were estimated by the filtbank function for each recording day as the mean value of a 30 s noise recording with no ships nearby. Although a 30 s window to quantify ambient noise is not ideal, this was the best available estimate of ambient noise levels, as all the recording areas were heavily ship-trafficked (Fig. 1). Ambient noise levels were corrected for the decreasing hydrophone sensitivity at frequencies above 80 kHz for the TC4032 and the B&K 8101 hydrophones.

To ensure that recordings genuinely represented noise from the ships, a signal-to-noise ratio (SNR) criterion was defined; "*signal*" being the vessel noise of interest and "*noise*" being the ambient noise or self-noise, whichever dominated. The criterion was set to 10 dB for each third-octave band as an indicator for a substantial elevation above ambient noise level. Only recordings fulfilling this criterion were included in further analysis, i.e., when RTOLs $\geq$ ambient/self-noise $+10$ dB (corresponding to values above the $M2$ lines in Fig. 2).

D. Vessel noise levels in MSFD bands

To test whether the two low-frequency MSFD bands around 63 and 125 Hz can be used as proxies for the vessel noise level at higher frequencies, the RTOLs at 63 and 125 Hz were compared with RTOLs at 1, 10, and 125 kHz. In order to test also the relationship between the MSFD bands and the total noise level at higher frequencies, RTOLs were summed for frequencies from 500 Hz to 160 kHz and compared with the 63 and 125 Hz RTOLs. The summed RTOLs were estimated for the time of CPA and included all 20 vessel passages that fulfilled the 10 dB signal-to-noise criterion described above for both third-octave bands compared. For each comparison a linear regression was performed on a log-scale and the explained variation was expressed as R^2.

E. Impact assessment for harbor porpoises

The potential for the vessel noise to mask important acoustic signals for harbor porpoises can be estimated with the passive sonar equation (Urick, 1983). By this equation, the available area where an animal can detect signals in noise at a given SNR can be estimated from the source level (SL) of the signal, the transmission loss (TL), the noise (N), and the directivity index (DI) of the animal's hearing system given by the frequency specific parameters of the passive sonar equation:

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{TL} - \mathrm{N} + \mathrm{DI}.$$

The TL can be modeled as spherical spreading plus excess attenuation due to absorption α, under the assumption that porpoise signals experience spreading according to the inverse square law (DeRuiter *et al.*, 2010):

$$\mathrm{TL} = 20\log\left(\frac{R}{1m}\right) + \alpha R, \ \text{where } R \text{ is range in meters.}$$

The noise term N covers all external noise sources, the ambient noise, and any masking noise, such as a passing ship, which may add on top of the ambient noise. Receiver directivity (DI) is ignored in the following, since the decrease in SNR is the same, independent of the spatial orientation of the listening animal. An animal affected by noise from a passing ship may obtain release from masking by changing its orientation relative to the ship, but this compensating behavior does not change the fact that the ship noise affects the detection capabilities of the animal.

Whenever an animal is listening for a particular sound in noise, there is a certain minimum SNR, depending on the task of the animal, which the auditory system requires to evaluate the sound. The most fundamental task, detection of a sound, can be performed at the lowest SNR. A higher SNR is required for animals to localize and identify the sound, and an even higher SNR is required in order to extract relevant information about the source of the sound (Green and Swets, 1966). Whatever task the animal seeks to solve by means of the sound, there is thus a threshold signal-to noise-ratio, $\mathrm{SNR}_{\mathrm{thr}}$, below which the task is not possible to complete. For a given sound source with a given SL this translates into a maximum communication range $R_{\max}$, where the following is fulfilled:

$$\mathrm{SL} - \mathrm{TL} - \mathrm{N} = \mathrm{SNR}_{\mathrm{thr}},$$

$$\text{where } \mathrm{TL} = 20\log R_{\max} + \alpha R_{\max}.$$

If masking noise ($\mathrm{N}_{\mathrm{ambient+ship}}$) is added, the maximum communication range is reduced from $R_{\max}$ to $R'_{\max}$. As the required $\mathrm{SNR}_{\mathrm{thr}}$ is the same in both cases, this implies:

TABLE I. Characteristics of the 17 recorded ships (one ship recorded on two occasions and one ship on three occasions), and the nearest other ship at the time of closest approach for each recording. MMSI-number, type and speed were obtained from AIS data. Year, weight, length, width, draught, propulsion and power were obtained from marinetraffic.com with additional information from fleetmon.com, shipspotting.com, nok-schiffsbilder.de and hafenradar.de. NA = not available.

Vessel specifications and recording details										Nearest other vessel at CPA time			
	MMSI	Type	Year built	Weight (GT)	Length × width; draught	Propulsion	Power (KW)	Speed (km/h)	CPA distance (m)	MMSI	Type	Speed (km/h)	Distance (m)
1	*219 601 000*	Fast ferry	1998	5617	91 m × 26 m; 3.8 m	Jet	28 320	77.6	220	304 771 000	Cargo	8.1	5130
2	*219 601 000*	Fast ferry, same as no. 1	—	—	—	—	—	77.8	360	305 600 000	Container	12.6	2170
3	*209 405 000*	Conventional ferry	1996	14 379	133 m × 24 m; 6 m	Propeller	11 637	30.0	100	304 771 000	Cargo	6.1	2610
4	*219 702 000*	Fast ferry	1996	3971	76 m × 23 m; 3.6 m	Jet	24 800	67.4	490	305 600 000	Container	0.0	2470
5	*309 681 000*	Reefer	1994	7743	131 m × 18 m1; 6.7 m	Propeller	NA	23.5	390	311 045 200	Cargo	21.3	2940
6	*311 045 200*	Cargo	1993	2446	87 m × 13 m; 3.5 m	Propeller	NA	21.1	1090	*309 681 000*	Reefer	26.5	3070
7	*311 701 000*	Cement carrier	1973	3067	99 m × 17 m; 5.8 m	Propeller	1530	25.0	1200	311 045 200	Cargo	22.2	5320
8	*305 661 000*	Cargo	1987	1593	82 m × 12 m; 2.9 m	Propeller	599[2]	14.4	150	NA	Navy ship	0.4	3730
9	*256 208 000*	Conventional ferry	1981	37 301	200 m × 28 m; 8.5 m	Propeller	10 635	23.7	240	NA	Navy ship	1.3	3490
10	*548 652 000*	Bulk carrier	2003	30 011	190 m × 32 m, 6.2 m	Propeller	7800[3]	28.9	1170	664 296 000	Oil/chemical tanker	25.9	3530
11	*664 296 000*	Oil/chemical tanker	2005	22 346	185 m × 28 m; 10.5 m	Propeller	NA	27.6	980	548 652 000	Bulk carrier	27.0	3150
12	*325 423 000*	Cargo	1967	1064[4]	69 m × 11 m; 3.7 m	Propeller	NA	19.8	1010	249 246 000	Oil/chemical tanker	23.5	4540
13	*249 246 000*	Oil/chemical tanker	2009	11 935	144 m × 23 m; 6.5 m	Propeller	NA	25.0	1070	325 423 000	Cargo	18.1	3100
14	*219 017 081*	Fast ferry	2009	10 503	112 m × 30 m; 3.3 m	Jet	36 000	70.0	210	219 601 000	Fast ferry	70.9	7350
15	*219 017 081*	Fast ferry, same as no. 14	—	—	—	—	—	70.4	90	219 601 000	Fast ferry	69.6	6990
16	*NA*	Navy ship	NA	246	43 m × 9 m; 3 m	Propeller	4200	43.0	110	*219 017 081*	Conventional ferry	28.3	6690
17	*219 017 081*	Fast ferry, same as no. 14	—	—	—	—	—	69.3	60	219 001 226	Cargo	13.9	10 320
18	*21 997 000*	Tender	2002	798	45 m × 10 m; 3.3 m	Propeller	1498	17.4	920	219 000 577	Conventional ferry	23.7	4690
19	*566 275 000*	Bulk carrier	1998	25 889	187 m × 29 m; 9.6 m	Propeller	NA	25.2	1190	NA	Navy ship	34.1	5270
20	*NA*	Navy ship	NA	185	43 m × 9 m; 2.6 m	Propeller	2100	34.3	960	219 159 000	Tug	21.5	8690

$$
\begin{aligned}
&\mathrm{SL{-}TL{-}N_{ambient}} = \mathrm{SNR_{thr}} = \mathrm{SL{-}TL{-}N_{ambient+ship}}\\
&\qquad\qquad\quad\Updownarrow\\
&20\,\log R_{\max} + \alpha R_{\max} + \mathrm{N_{ambient}} = 20\,\log R'_{\max} + \alpha R'_{\max}\mathrm{N_{ambient+ship}}\\
&\qquad\qquad\quad\Updownarrow\\
&20\,\log R_{\max} + \alpha R_{\max} - 20\,\log R'_{\max} - \alpha R'_{\max} = \mathrm{N_{ambient+ship}{-}N_{ambient}}\;.\\
&\qquad\qquad\quad\Updownarrow\\
&20\,\log \frac{R_{\max}}{R'_{\max}} + \alpha\left(R_{\max} - R'_{\max}\right) = \mathrm{N_{ambient+ship}{-}N_{ambient}}
\end{aligned}
$$

Now, a range reduction factor (Møhl, 1981) can be defined, which is simply the ratio of $\mathrm{R_{max}}$ to $R'_{\max}$. Put in another way, if the noise level (N) in the environment increases, assuming a constant SL, decreasing TL is the only way the same SNR can be maintained. A decrease in TL will then translate to a shorter communication range ($R'_{\max}$) compared to the communication range in the absence of the noise ($R_{\max}$). This relative decrease in active space, where an animal can utilize passive hearing to gain information about the environment, is then quantified as the range reduction factor (Møhl, 1981; Jensen *et al.*, 2009). A range reduction factor of 1, equal to 0 dB ($20\,\log(R_{max}/R'_{\max})$) means that the masking noise has no effect on the communication range, whereas an infinite range reduction factor means that communication range has decreased to zero (communication impossible at all ranges). The range reduction factor is given from the above as:

$$
\begin{aligned}
\frac{R_{\max}}{R'_{\max}} &= 10^{\left(\mathrm{N_{ambient+ship}{-}N_{ambient}} - \alpha\left(R_{\max} - R'_{\max}\right)\right)/20}\\
&= \frac{10^{\left(\mathrm{N_{ambient+ship}{-}N_{ambient}}\right)/20}}{10^{\alpha\left(R_{\max} - R'_{\max}\right)/20}}\,.
\end{aligned}
$$

This equation is difficult to handle at high frequencies because of absorption. However, if the range reduction is small or absorption can be ignored, as it can for lower frequencies, then $\alpha(\mathrm{R_{max}} - R'_{\max}) \approx 0$ and the range reduction factor becomes range independent:

$$
\begin{aligned}
&20\,\log\left(\frac{R_{\max}}{R'_{\max}}\right) = \mathrm{N_{ambient+ship}{-}N_{ambient}}\\
&\Longleftrightarrow \frac{R_{\max}}{R'_{\max}} = 10^{\left(\mathrm{N_{ambient+ship}{-}N_{ambient}}\right)/20}\,.
\end{aligned}
$$

If these assumptions are fulfilled and as long as the signal in question propagates by spherical spreading, a tenfold increase in the noise level (=20 dB) results in a tenfold reduction in range, independent of whatever maximum range the animal is capable of communicating across before the masking noise is added. For this situation, range reduction in dBs can be translated to a relative reduction in active range on a linear scale, which is the range reduction factor. However, if the absorption is considerable, as it is for higher frequencies, the range reduction instead becomes range specific, and cannot be translated to a simple factor.

The impact of vessel noise on porpoises was assessed by using the actual recorded RLs ($\mathrm{N_{ambient+ship}}$) at the recording stations to calculate the range reduction, which is thus an estimate of how the active space for a porpoise decreases as a result of exposure to vessel noise. The elevation in noise level ($\mathrm{N_{ambient+ship}}$ - $\mathrm{N_{ambient}}$) is thereby representative for the increased ambient noise level a porpoise at the same range will experience. To guarantee that it was the ship noise rather than ambient or self-noise which was evaluated, only RTOLs at least 10 dB above both self-noise and ambient noise were used. Additionally, as the hearing sensitivity of harbor porpoises is available (Kastelein *et al.*, 2002; Kastelein *et al.*, 2010) situations, where the animal would be limited by its hearing system rather than the ambient noise, could be taken into account. Only RTOLs 3 dB or more above the porpoise audiogram were included. Noise above this level has previously been assumed to cause acoustic masking (Jensen *et al.*, 2009). Ultimately the range reduction can be calculated by:

$$
\frac{R_{\max}}{R'_{\max}} = 10^{\left(\mathrm{N_{ambient+ship}{-}N_{limit}}\right)/20},
$$

where $\mathrm{N_{limit}}$ is either the ambient noise level or the hearing threshold of the porpoise, whichever is the limiting factor at the particular range from the noise source.

Impact assessment by estimation of range reductions was conducted for three third-octave bands. The first band was centered at 1 kHz, which is in the lower frequency range of porpoise hearing (Kastelein *et al.*, 2002; Kastelein *et al.*, 2010), but in a frequency range where substantial contributions of vessel noise to ambient noise levels are expected (Wenz, 1962; National Research Council, 2003). The second band was centered at 10 kHz, which is the upper limit indicated for the noise contribution of ship activity according to the Wenz curves (Wenz, 1962), and in a frequency band where porpoises have a relatively good hearing. The third band was centered at 125 kHz, which is the frequency range where porpoises have their most sensitive hearing (Kastelein *et al.*, 2002; Kastelein *et al.*, 2010) and where they produce clicks for echolocation (Møhl and Andersen, 1973) and communicate (Clausen *et al.*, 2010). For the 1 and 10 kHz bands, where absorption could be ignored, the resulting *range reduction factor* was estimated. However, for noise in the 125 kHz band absorption is considerable and the range reduction therefore cannot be translated to a factor, and the value was only expressed in dBs. The following example illustrates how absorption affects the relative reduction. If two porpoises are just able to communicate when 50 m apart, and the noise is elevated by 20 dB, the animals can compensate this loss of SNR by moving a factor 10 closer, i.e., to

5 m apart, as absorption at short ranges can be ignored [TL ≈ 20log(10) = 20 dB]. However, if the two porpoises are instead 500 m apart and just able to communicate, and again exposed to an elevation in noise of 20 dB, then moving a factor 10 closer to each other will result in a reduction in TL of 20 dB + some dBs due to absorption. Assuming an absorption coefficient of 40 dB/km for a 125 kHz sound, then moving from 500 to 50 m will further reduce the TL by 18 dB (0.04 dB/m · 450 m), which means that the SNR at 50 m is now 18 dB higher, even with the masking noise, than at 500 m without the masking noise. This means that the range at which the porpoises are able to communicate in the noise is not 50 m (a factor 10 closer), but instead roughly 200 m. The high absorption thus reduces the masking potential of the ship noise at high frequencies.

III. RESULTS

Twenty broadband noise recordings from 17 different vessels were made at ranges between 60 and 1200 m. Table I summarizes vessel specifications and noise recording details. For estimations of masking impacts on porpoises, vessels were divided into three categories: (1) Ferries, (2) freighters, and (3) navy ships. The category "freighters" also included a tender (ship no. 18, Table I).

A. Vessel noise received levels

For each vessel passage the received sound pressure levels were calculated for 39 third-octave bands (center frequencies from 0.025 to 160 kHz). RTOLs are shown in Fig. 2 along with representative ambient noise levels for each recording day, and the self-noise of the hydrophones used for the recordings.

In Southern Kattegat [Figs. 2(a) and 2(b)] all vessels, measured at distances between 60 and 490 m, caused substantial elevation of ambient noise over a broad frequency range. Third octave noise levels reached 114 dB re 1 μPa (rms) at 125 kHz [ship no. 16 recorded at 110 m, Fig. 2(b)], which was 50 dB above ambient noise level in this frequency band. In the Great Belt [Figs. 2(c) and 2(d)] ambient noise levels were generally higher compared to the two areas in Southern Kattegat due to a consistently high shipping intensity. Noise levels in the frequency range 25 Hz to 40 kHz in the Great Belt in November [Fig. 2(d)] were substantially elevated (97 dB re 1 μPa rms at 40 kHz, 14 dB above ambient), when a ship passed at a distance of 1190 m (ship no. 19). The RTOLs varied among the vessels, likely as a result of different ship types, different distances to the receiver, and oceanographic conditions that affected propagation in the four recording areas. Of the 17 different vessels recorded only 1 had the highest noise level in one of the two MSFD bands [ship no. 16, 130 dB re 1 μPa rms at 125 Hz, Fig. 2(b)]. For all other vessels, the RTOLs peaked at other frequencies. Small jet ferries [ship nos. 1, 2, and 4, Fig. 2(a)] emitted the highest levels of noise at 500 and 1000 Hz, whereas the larger jet ferry [ship nos. 14, 15, and 17, Fig. 2(b)] emitted the most noise in the 100 and 500 Hz third-octave bands. Ten freighters [ship nos. 5–8, 10–13, 18–19, Figs. 2(c) and 2(d)], two propeller-driven ferries [ship nos. 3 and 9, Figs. 2(a) and 2(c)], and a navy ship [ship no. 20, Fig. 2(d)] had the highest RTOLs at frequencies ≤100 Hz. Multiple recordings of two fast ferries (ship nos. 1 and 2 and ship nos. 14, 15, and 17) resulted in similar noise profiles within each ship [Figs. 2(a) and 2(c)].

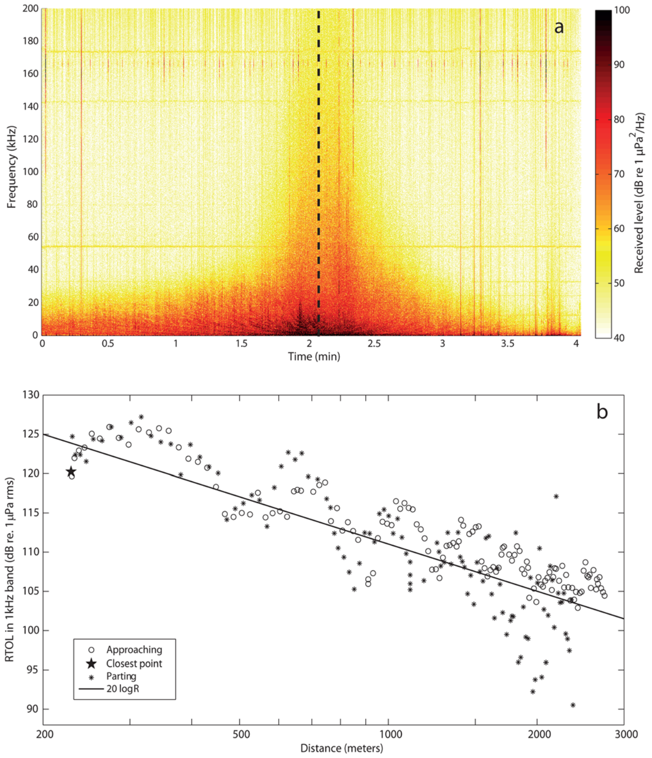

FIG. 3. (Color online) Passage of a fast ferry (no. 1, Table I): (a) Spectrogram, the time of CPA is marked with a dashed vertical line, (b) The RTOLs in the 1 kHz third-octave band recorded for the passage during approach (circles) and distancing (stars). The line indicates predicted TL from simple spherical spreading.

Figure 3 shows the received noise levels measured from the passage of ship no. 1 (fast ferry) from approximately 2 min before CPA time to about 2 min after. There was an overall good correlation between range to the ship and recorded levels of noise, confirming that the elevated noise levels are caused by emission from this specific vessel [Fig. 3(a)]. The levels of high frequency noise peaked around CPA time, consistent with the otherwise considerable absorption losses being smaller at shorter ranges. However, the noise at 1 kHz did not peak at the closest range [220 m, Fig. 3(b)], but instead when the ship was approximately 130 m further from the recording station. Overall trend in noise level with distance followed the predictions of simple spherical spreading loss, but with substantial variation. At a range of 2 km, noise levels varied within at least 20 dB for even small changes in distance [Fig. 3(b)].

B. MSFD bands as proxies for broadband vessel noise

The use of the low-frequency MSFD bands, 63 and 125 Hz, as proxies for vessel noise at higher frequencies was tested (Fig. 4). For the frequency bands 1 and 10 kHz there was a very poor correlation with the 63 Hz band [R^2 of 0.019

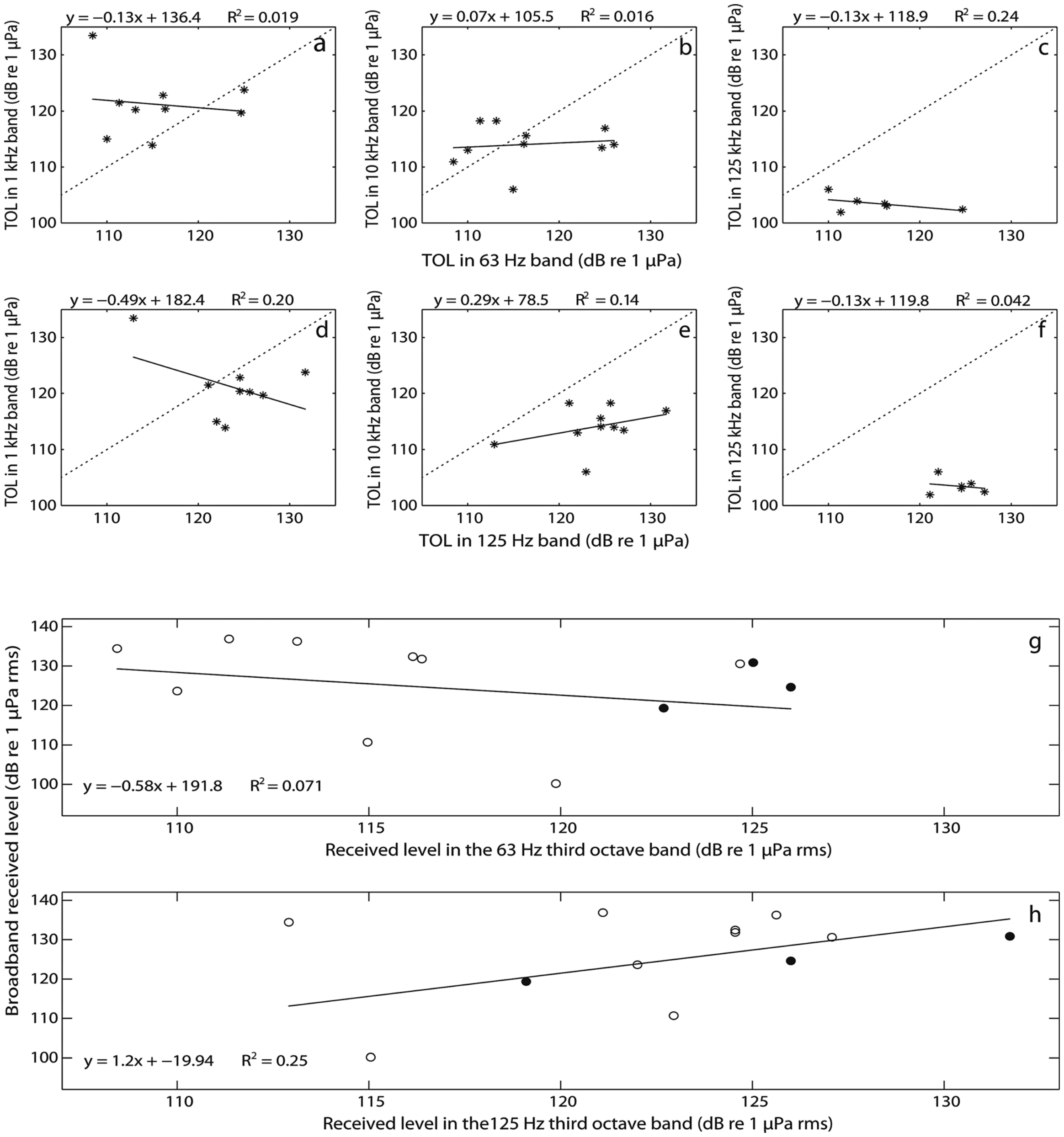

FIG. 4. The relationship between noise in the low-frequency MSFD bands, 63 and 125 Hz, and noise levels at higher frequencies for different vessels: [(a)–(f)] Correlations between the two MSFD bands and third-octave bands 1, 10, and 125–kHz, [(g) and (h)] correlations between the two MSFD bands and broadband noise levels above 500 Hz. Open circles are broadband levels from 500 Hz to 160 kHz, while the filled circles are bandlimited at 12.5 kHz, because of high frequency noise interference.

and 0.016; Figs. 4(a) and 4(b)], whereas the 125 Hz MSFD band had a somewhat better correlation [R^2 of 0.20 and 0.14; Figs. 4(d) and 4(e)]. The opposite pattern was seen for the 125 kHz band, where the correlation coefficient (R^2) for the 63 Hz band was 0.24 compared to 0.04 for the 125 Hz band [Figs. 4(c) and 4(f)].

To compare the broadband noise level with the RTOLs in the 63 and 125 Hz MSFD bands, the third-octave levels from 500 Hz to 160 kHz were summed. Twelve ships, where the ship noise was at least 10 dB above the ambient noise, were included in the analysis [Figs. 4(g) and 4(h)]. Results show that the MSFD band at 125 Hz [R^2 of 0.25; Fig. 4(h)] was a better proxy for the total noise at higher frequencies than the 63 Hz band [R^2 of 0.07; Fig. 4(g)]. However, there was still up to 35 dB variation in the broadband noise level for a given noise level in the 125 Hz band [Fig. 4(h)].

C. Impact assessment for harbor porpoises

The estimated range reduction (in dB and %) for harbor porpoises in the three third-octave bands (1, 10, and 125 kHz) caused by noise emission from the 20 recorded vessel passages are shown in Fig. 5. Estimations were based on actual received noise levels and under the assumption that a porpoise placed at the same location as the recording hydrophone would have experienced the same noise levels as those recorded. The effect of recording range, ship size, type, and speed on the reduction in range is also included in Fig. 5.

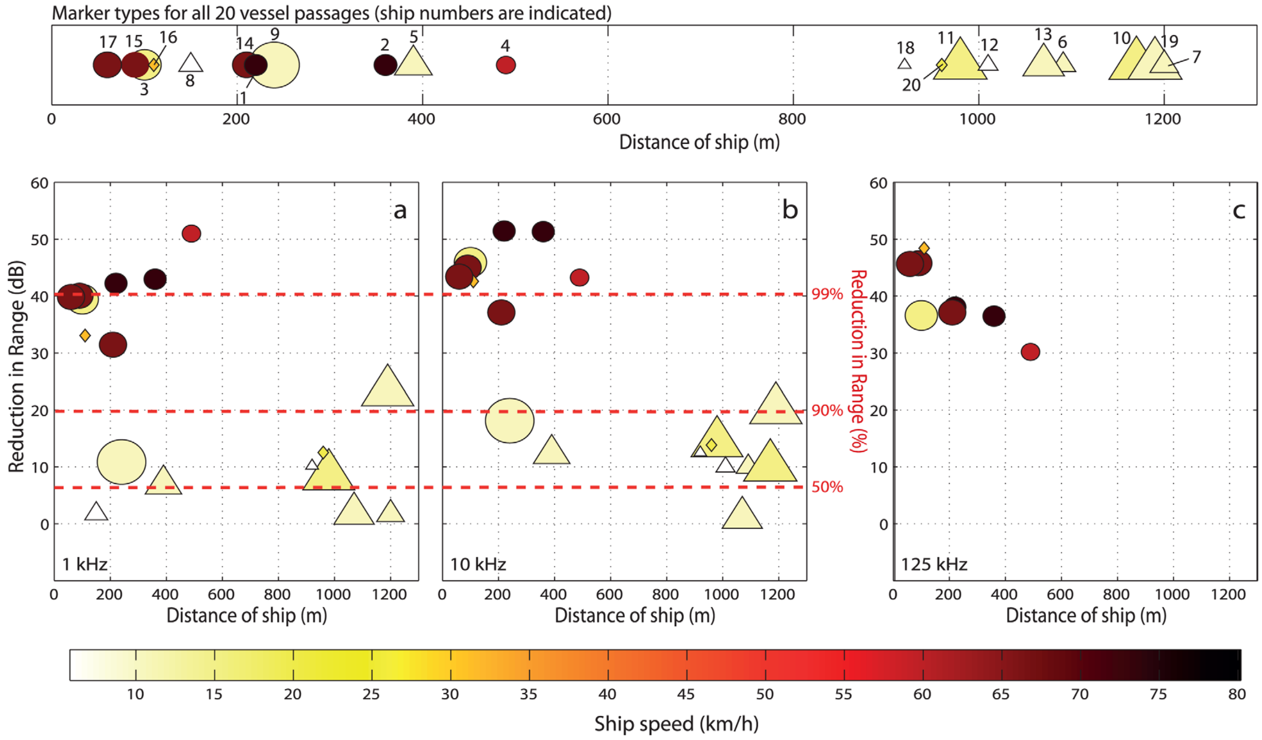

FIG. 5. (Color online) Acoustic masking impacts on harbor porpoises as a result of vessel noise in three third-octave bands (1, 10, and 125 kHz) modeled as the "reduction in range (dB)." Only vessels emitting noise ≥ 10 dB above ambient noise levels, self-noise levels, and the porpoise audiogram were included. The position of each marker (corresponding to a ship) indicates the distance and masking effect. Shape indicates ship type: circles = ferries, triangles = freighters, diamonds = navy ships. Size indicates the relative size of the ship. Brightness indicates ship speed (km/h, see color bar). For the 1 and 10 kHz the range reduction in dB could be translated to the percentage of lost range as absorption was ignored. For the 125 kHz band absorption losses are considerable and range reduction could not be translated in a simple way to a percentage loss.

For the two third-octave bands 1 and 10 kHz [Figs. 5(a) and 5(b)] absorption losses were considered negligible, and therefore the range reductions could be translated into a percentage of range reduction. For example, a 6 dB elevation in ambient noise levels will decrease the hearing range of a porpoise with 50%, a 20 dB rise in ambient noise corresponds to a tenfold increase in noise level and hence a 90% range reduction, and a 40 dB rise in ambient noise means a reduction in range down to 1% for the animal [Figs. 5(a) and 5(b)].

For the 1 kHz third-octave band [Fig. 5(a)], 17 vessels were estimated to affect the porpoise hearing range substantially, and of these 14 vessels were estimated to cause more than 50% reduction in range. Three of these vessels reduced hearing range by more than 90%, and 6 ferry passages recorded within 500 m were estimated to have caused a severe range reduction of around or above 99%. The largest noise impact at 1 kHz was seen for the fast ferry recorded at 490 m range (ship no. 4), where range reduction exceeded both the larger and faster ferry at closer range (ship nos. 1 and 2, 220 and 360 m, respectively). The estimates for range reductions in the 10 kHz third-octave band [Fig. 5(b)] showed a similar pattern as the 1 kHz band, with smaller noise impacts from the slower vessels than the fast ferries. Perhaps surprisingly, the potential noise impact predicted from the fast ferries within 400 m range (ship nos. 1, 2, 14, 15, and 17), a propeller-driven ferry (ship no. 3), and a navy ship (ship. no. 16) was higher by up to almost 10 dB in the 10 kHz band, compared to in the 1 kHz band [Fig. 5(a)]. The largest noise impact at 10 kHz of 50 dB, translating to well above a 99% loss, was seen for the two passages of the same fast ferry (ship nos. 1 and 2) recorded at ranges of 220 and 390 m [Fig. 5(b)]. In the 125 kHz band 8 ship passages, comprising 3 fast ferries (ship nos. 1 and 2, ship no. 4, and ship nos. 14, 15, and 17), a propeller-driven ferry (ship no. 3), and a navy ship (ship no. 16), were estimated to cause a range reduction for porpoises by increasing the noise level with 30 dB for recordings out to a range of 490 m (ship no. 4). A navy ship recorded at a range of 110 m (ship no. 16) caused the highest estimated noise impact with almost 50 dB in the 125 kHz band [Fig. 5(c)].

IV. DISCUSSION

Shipping noise from all 20 vessel passages recorded in this study were substantially above ambient noise across a broad frequency range from 25 Hz up to 160 kHz. This implies that the noise has potential to impact not only marine mammals with good low frequency hearing, but also high frequency specialist such as harbor porpoises and other small toothed whales. Furthermore, it calls for re-evaluation of the usefulness of the low frequency bands as indicators for ship noise and proxies for broadband levels, such as the currently designated bands at 63 and 125 Hz within the European MSFD.

A. High frequency vessel noise

The noise recordings conducted in four shallow water areas (15–20 m depth) revealed elevations in ambient noise well above 10 kHz from vessels recorded at ranges out to

1190 m, which are overlapping with frequency bands biologically relevant for small toothed whale species, such as harbor porpoises. Even in the third-octave band at 125 kHz, where the frequency dependent absorption is very high, substantially elevated noise levels were seen in at least 8 vessel passages. Several of the remaining vessels likely generated elevated noise levels also at 125 kHz, but conclusions were precluded by self-noise limitations of the recording gear at these high frequencies.

One of the recorded vessels was a jet propulsion ferry, which caused a 36 dB increase in the 125 kHz band at a range of 360 m (ship no. 2). Two other jet-driven ferries (ship no. 4 and ship nos. 14, 15, and 17) also emitted substantial levels of noise in the 125 kHz band. Water jets have been considered a quieter propulsion system than propellers (Southall and Scholik-Schlomer, 2008), yet this study shows that vessels driven by water jet propulsion can emit substantial levels of high frequency noise, which may exceed the noise levels of propeller-driven vessels within the same range. However, the main explanation for the high levels recorded from the jet ferries in this present study is a closer recording range of these vessels compared to other vessels and hence a smaller effect of the large frequency dependent absorption at close range. Thus, noise contributions at 125 kHz from propeller-driven vessels are likely also to be substantial at closer ranges than the recording ranges used in this study. Noteworthy is that the largest jet ferry (ship nos. 14, 15, and 17) emitted approximately the same amount of noise as the smaller jet ferries (ship nos. 1, 2, and 4) (Fig. 2), despite a three times larger carrier capacity. Thus, the noise load per transported car is considerably lower for the large ferry than for the smaller ferries (ship nos. 1, 2, and 4).

These recordings show that the vessels produce different acoustic signatures, consistent with common experience (e.g., National Research Council, 2003; McKenna *et al.*, 2012). Previous studies have indicated that levels of low frequency noise are positively correlated with size and speed of the vessel (Ross, 1976; Arveson and Vendittis, 2000; McKenna *et al.*, 2013). Our results suggest that high ship speeds can also cause increased noise levels at high frequencies. This is in accordance with previous studies reporting increased medium-to-high frequency cavitation noise with increased speed (Aguilar Soto *et al.*, 2006; Jensen *et al.*, 2009), and that cavitation noise at high speeds can become more dominant than the low frequency machinery noise (National Research Council, 2003). However the acoustic signature is affected by several vessel specifications, such as size, speed, propulsion type, and load (Jensen *et al.*, 2009; McKenna *et al.*, 2012; McKenna *et al.*, 2013), which are often inter-related. Large size is linked to large engines and jet propulsion is usually linked to high speeds. It is therefore difficult to identify a single, critical parameter for predicting ship noise signatures, although good correlations often can be obtained within ship types and especially for deep water signatures (Ross, 1976).

Besides ship characteristics, the acoustic signature recorded at a given range may also be influenced by interference patterns due to multiple radiation points from the ship and multipath propagation. The large fluctuations in received noise levels around the time of CPA for ship no. 1 (Fig. 3) were likely due to such constructive and destructive interference. Interference patterns vary according to the depth and range of source and receiver, bathymetry, sediment composition, the sound velocity profile, and the fact that the ship at close ranges can no longer be considered a point source. The result is pronounced variation in actual recorded levels compared to predictions from a simple geometric spreading model (see also McKenna *et al.*, 2012).

At low frequencies, the fluctuations in RTOLs are likely at least in part caused by the shallow water, which does not support transmission of the low frequency modes (Forrest *et al.*, 1993). In shallow water with constant depth, no temperature gradient and a rigid bottom, the wavelength of the cutoff frequency will be 4 times the depth of water (Kinsler *et al.*, 1982). So, for a water depth of 15 m, the cutoff frequency would be 25 Hz, whereas the cutoff frequency with a depth of 5 m would be 70 Hz, thereby impeding propagation of sound in the 63 Hz band. If there is a temperature gradient or a sandy bottom, as in the study areas here, additional low frequency noise will be lost (National Research Council, 2003). Besides interference phenomena, some variation may also be explained by the uncertainty associated with averaging low frequency sounds over the period of 1 s. At 100 Hz the uncertainty for a third-octave average of 1 s of Gaussian noise is approximately ±2 dB, whereas it is more than 5 dB at 25 Hz, due to fewer degrees of freedom (Brüel and Kjær, 1986).

So because of the complex propagation patterns both at very high and very low frequencies, the noise levels around a moving ship in shallow water are very difficult to predict. Consequently, noise levels from vessels should be measured rather than modeled in shallow water habitats, especially when the aim is to estimate noise exposure to animals in the area.

B. Implications for the European MSFD

The European MSFD focuses on low frequency vessel noise as pressure indicators for ship noise, more specifically the two third-octave bands around 63 and 125 Hz (European Commission, 2010; descriptor 11). The two bands were selected based on recordings of ship noise in deep-water areas, where noise in general is most powerful in these bands (Ross, 1976; National Research Council, 2003). However, harbor porpoises have very poor hearing below 500 Hz, so for the MSFD bands at 63 and 125 Hz to serve as suitable pressure indicators for noise of relevance for porpoises, there must be a consistent and reliable relationship between noise levels in these two bands and noise levels at higher frequencies of direct relevance to porpoises and other small toothed whales living in shallow waters.

Our recordings show that only 1 out of 20 vessels had a peak in the noise signature in one of the MSFD bands. This in itself is not an argument against the MSFD bands, as the signatures are affected highly by propagation conditions and the peak frequencies are likely to change with range for the same ship. The real issue is that energy in both MSFD bands correlated very poorly with ship noise in third-octave bands centered at higher frequencies: 1, 10, and 125 kHz and also correlated poorly with broadband levels above 500 Hz. The error when predicting broadband noise levels from measured noise level in the 125 Hz band was up to 35 dB and for the 63 Hz band there was no useful correlation at all. The large residual variation is attributed to the large variation in the vessels recorded, both in terms of vessel characteristics and environmental factors of the recordings. In other more shallow habitats, the propagation of noise in the 125 Hz third-octave band is likely to be further impeded, which means that it will be even less useful as a proxy for noise levels at higher frequencies. Neither of the two current MSFD bands therefore seems reliable proxies for vessel noise at higher frequencies in shallow water. These frequency bands are thus poorly suited to estimate ship noise levels at frequencies that matter to porpoises and other small toothed whales. It thus seems prudent to include information about frequencies well above the 63 and 125 Hz bands, when assessing environmental status with respect to noise in shallow waters for animals with poor low frequency hearing.

Which measure could then be used to supplement the 63 and 125 Hz bands and allow better assessment for animals such as porpoises? The absorption at higher frequencies complicates identification of a suitable frequency band for high frequency species, as noise at these frequencies does not propagate far and may correlate poorly with noise at intermediate frequencies that propagate further and are still within the frequency range where porpoises have good hearing. Thus, rather than selecting a band at very high frequencies, where the hearing of porpoises is most sensitive (i.e., the 125 kHz band), we propose that vessel noise is quantified in the third-octave band at 10 kHz, as a compromise between a frequency that is still high enough for the hearing sensitivity of small toothed whales to be good, a frequency low enough for the frequency dependent absorption to be insignificant (<0.1 dB/km), and yet not so low that the wavelength precludes propagation in shallow water. Furthermore, even though there is a continuous and fast development in recording equipment, the choice of the 10 kHz band would mean that most of the currently available equipment will be immediately usable.

C. Potential effects on porpoises

The medium-to-high frequency ship noise recorded in shallow water at considerable ranges clearly was at levels where effects on harbor porpoises could be expected. Based on previous studies of noise impacts on this species, the potential for the noise to affect behavior, mask the hearing, and cause injury to the hearing system can be assessed.

1. Behavioral responses

Harbor porpoises have been shown to change behavior in response to a range of different underwater noise sources, with most observable reactions being avoidance. These studies include reactions to pingers (20–160 kHz) at ranges of 100–200 m (e.g., Culik *et al.*, 2001), seal scarers (10–14.5 kHz) at ranges between 1 and 7.5 km (e.g., Johnston, 2002; Brandt *et al.*, 2013) and pile driving noise, which has most energy at low frequencies but at very high levels, up to 20–25 km away (e.g., Tougaard *et al.*, 2009; Dähne *et al.*, 2013). Less well studied are reactions to ships, but avoidance at ranges to 800–1000 m has been reported (Barlow, 1988; Palka and Hammond, 2001). Our results show that noise levels are substantially elevated at ranges out to at least 1190 m for the low and mid-frequency bands (1 and 10 kHz) and out to at least 490 m for the high frequency bands (125 kHz), where porpoises have their most sensitive hearing. Thus, the prerequisites for adverse vessel noise effects on porpoises were present in these four shallow water habitats at considerable ranges. These relationships of what frequency specific noise levels might initiate adverse behavioral reactions in porpoises and the ranges of such effects can hopefully be elucidated in the future, by use of acoustic tags on free-swimming animals (Johnson and Tyack, 2003).

2. Masking

Acoustic masking has previously been highlighted as the primary effect of vessel noise on cetaceans (Møhl, 1981; Southall *et al.*, 2007). Masking, manifested as a decreased ability to detect signals with increasing noise, can be studied readily on captive animals with behavioral methods (e.g., Johnson, 1968; Erbe and Farmer, 1998; Kastelein *et al.*, 2009). For wild animals it is much more difficult to demonstrate and quantify acoustic masking, as masking may not cause observable behavioral responses, such as displacement or alterations in signal characteristics. When dealing with masking on wild animals, a lack of response is accordingly not equal to an absence of masking. Rather, by its very nature, masking is likely leading to an absence of behavior: Failure in detecting a conspecific, potential prey or predator, which in turn could have serious impacts on fitness of the animal.

Masking effects were here estimated from measured third-octave levels and quantified as range reductions for porpoises exposed to the same noise, i.e., located at the same position as the recording hydrophone. This approach ignores behavioral reactions the animal could potentially perform in order to obtain release from masking release, such as reorienting or increasing vocalizations in communication or echolocation (Lombard response). Such behaviors may fully or partly reduce the masking experienced in the given situation, but this does not alter the fact that the auditory scene of the animal has been altered in proportion to the change in noise levels, as long as the noise exceeds the hearing threshold (Clark *et al.*, 2009). The range reduction factor is therefore a good general estimate of the relative decrease in range over which an animal can operate acoustically, when exposed to noise (Møhl, 1981; Jensen *et al.*, 2009).

Our results show that ship noise is able to cause severe range reductions for porpoises: More than 90% within a distance of 1190 m in the third-octave bands of 1 and 10 kHz. In the high frequency band at 125 kHz the decrease in SNR cannot be translated to a simple range reduction factor, as the frequency dependent absorption exceeds geometrical spreading losses at larger distances, rendering the relationship between TL and relative range change non-trivial. Nevertheless, it is clear that ships substantially elevated noise levels by 30 dB at a range of 490 m (ship no. 4) and between 35 and 50 dB for ships within 400 m from the recording platform. As an example of the potential masking by such noise elevations, consider the case of mother-calf communication in porpoises. The maximum communication range between mother and calf was estimated by Clausen *et al.* (2010) to be around 500 m. How would this range be affected by an elevation of ambient noise by 40 dB? In the unmasked condition the TL equals 74 dB [$20\log(500\,\mathrm{m}) + 0.04 \cdot 500\,\mathrm{m}$, assuming $\alpha = 40\,\mathrm{dB/km}$]. In the masked condition the TL must be 40 dB lower to compensate for the masker noise, i.e., only 34 dB. Solving the equation $20\log(r') + \alpha r' = 34\,\mathrm{dB}$ gives a masked maximum communication range ($R'_{\max}$) of only 40 m. This range reduction corresponds to an area in which mother and calf can maintain contact roughly 160 times smaller than the unmasked condition. In a worst case scenario, a 40 dB elevation in noise in the 125 kHz band would also cause a reduction in detection range of porpoise echolocation by an order of magnitude (Aguilar Soto *et al.*, 2006). Therefore, our results are indicative of possible severe, albeit short term, masking effects by ships at close range, up to a minimum of about 500 m. As self-noise was a limiting factor for measurements at high frequencies the range of potential impact from masking likely extended well beyond 500 m, but this could not be assessed.

3. Temporary threshold shift (TTS)

TTS is a temporary increase in the hearing threshold of an animal induced by noise exposure (Richardson and Malme, 1995). The hearing threshold returns to normal after a period which depends on the noise characteristics (most importantly intensity, frequency and duration; Finneran *et al.*, 2002; Kastelein *et al.*, 2012). A minimal amount of TTS (2.4 dB) has been induced in a captive harbor porpoise after exposure to 4 kHz octave band noise for 7.5 min at a sound pressure level of 124 dB re 1 μPa (rms), equal to at a cumulated sound exposure level (SEL) of 151 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$. (Kastelein *et al.*, 2012). The highest received levels recorded in this frequency range was from a fast ferry (ship no. 2), where 123 dB re 1 μPa (rms) was measured in the 4 kHz band at a range of 360 m. As this was measured in a third-octave band an additional 5 dB (10log3) should be added for comparison to the threshold by Kastelein *et al.* (2012). This comparison indicates that the porpoise of Kastelein *et al.* (2012), had it been at the position of the noise recordings, would have been unlikely to get TTS from the fast ferry noise around 4 kHz. To exceed the SEL of 151 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$ would require that the animal was within a few hundred meters of the fast moving vessel for several minutes. Nevertheless, TTS caused by exposure to a broadband noise source, such as vessel noise, may not be directly predicted by a TTS inflicted by narrowband noise as in the study by Kastelein *et al.* (2012). TTS induced by continuous exposure to broadband noise has been poorly studied and it is thus unclear how the energy at different frequencies should be combined. A recent study on the same porpoise used by Kastelein *et al.* (2012), but exposed to noise at lower frequencies (1–2 kHz), resulted in higher thresholds indicating that energy at lower frequencies may be less efficient in inducing TTS than at higher, more audible frequencies (Kastelein *et al.*, 2014). The relationship between the summed energy of noise exposures and TTS effects furthermore depend not only on the exposure levels, but also the number of noise exposures over time, which may be uncovered by use of acoustic tags in the future (Johnson and Tyack, 2003).

V. CONCLUSIONS

We have demonstrated that noise across a very broad frequency range, well into the ultrasonic, was emitted from different ship types, both propeller-driven and vessels with jet propulsion. Noise levels were sufficiently high for negative effects on harbor porpoises to be expected. In particular masking of communication and echolocation at close range, within 500 m and possibly further, appears as a cause for concern. In accordance with previous studies, we observed that different vessels had very different acoustic signatures and therefore different masking impact. Therefore, the best method to estimate the noise exposure to animals is recording broadband noise in relevant habitats. Modeling of noise impacts, based on noise SLs and propagation models, will depend heavily on the chosen vessel characteristics and environmental factors and should not solely be depended upon in noise impact assessments, but should be grounded in and verified by actual measurements.

The low-frequency third-octave bands around 63 and 125 Hz, highlighted in the MSFD as indicators of shipping noise, turned out to be poor proxies for the noise impacts at higher frequencies on small cetaceans. Consequently, higher frequencies should be included in assessment of good environmental status concerning smaller toothed whales. We propose that vessel noise is quantified in a third-octave band at 10 kHz, chosen as a compromise between hearing range of small toothed whales, calling for higher frequencies, and frequency dependent absorption, calling for lower frequencies where the absorption is small and hence transmission high.

In so-called "acoustic hotspots" (McCarthy, 2004), noisy anthropogenic activities overlap with important marine mammal habitats, resulting in an increased risk of adverse noise effects on marine mammal species. Behavioral reactions, acoustic masking, and TTS may all be short-term effects related to discrete exposures. However, with increased vessel activity in such hotspots, effects may occur many times a day. The fast ferries recorded in this study pass the same strait on average every 40 min in daytime on weekdays, and many hundreds of large vessels are present in Danish waters at any given time, as is the case for many other coastal waters worldwide. Therefore, even though the ranges at which high frequency noise levels are elevated are relatively small around each ship, repeated short-term exposures, each with only small effects, may accumulate and impact the long-term fitness of the affected animals. A single, isolated avoidance response may affect foraging time and increase energy expenditure only insignificantly, but cumulated over many responses, the combined effect on overall energy budget may be measurable. In the same way, a short period of acoustic masking or TTS may demand slightly more effort of the animal to find and catch prey, which may affect long-term fitness if the animal is repeatedly exposed to noise. Furthermore, even masking or TTS effects for only a short period of time can make an animal less attentive of the environment, in worst case resulting in failure to detect a predator or a gill net with fatal consequences. Thus noise effects that may seem negligible on the short term could potentially translate to serious long-term effects, with impacts on both individual fitness and population dynamics (National Research Council, 2005; Bejder *et al.*, 2006).

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