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Underwater noise impact of a ferry route on dive patterns of transiting Baltic ringed seals

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Abstract. To understand the impact of underwater anthropogenic noise on marine life, it is crucial to collect more data about the onset of behavioural reactions of marine species. Three free-ranging ringed seals (*Phoca hispida botnica*) were marked with GPS tags to track their movements in the Baltic Sea. The tracking data showed that ringed seals regularly transit between their haul-outs in the Väinameri and foraging areas in the southern part of the Gulf of Riga. On their way, the ringed seals pass through the Suur väin (Suur Strait) and have to cross the Virtsu–Kuivastu ferry route, where they are likely exposed to underwater ship-borne noise. Ringed seals' dive profiles were studied for the presence of avoidance reactions in response to ship-radiated noise. As a result, some dive profile irregularities were noticed in the form of deep dives or multiple surfacings. The received level (RL) causing the disturbance in ringed seals' behaviour was estimated based on sound propagation modelling. The obtained results are generally in line with previously reported studies on captive harbour seals and free-ranging grey seals. However, behavioural reactions observed in the current study are unlikely to adversely affect the energy budgets of ringed seals due to the short exposure time.

Keywords: underwater anthropogenic noise, ringed seals, disturbance behaviour, dive patterns.

1. INTRODUCTION

Ringed seals (*Phoca hispida*) can be found in all seasonally ice-covered seas of the Northern Hemisphere and in certain freshwater lakes. One of the habitats of the ringed seal subspecies, the Baltic ringed seal (*Phoca hispida botnica*), is the Gulf of Riga in the northern part of the Baltic Sea, where it is categorised as vulnerable and protected by the Habitats Directive (Helcom 2013). The main cause of this status is the reduction of the ice cover due to global warming, while the ice cover is essential for the breeding of ringed seals and specifically affects their pup survival (Sundqvist et al. 2012). Anthropogenic noise from increasing shipping density and off-shore construction in many marine regions, including the Baltic Sea, can be considered another environmental pressure impacting the ringed seal population (Russell et al. 2016; Sanjana et al. 2021).

Anthropogenic low-frequency continuous noise is known to be potentially detrimental to marine biota and in particular to pinnipeds (Erbe et al. 2019). As soniferous animals, pinnipeds rely on sounds for communication and hence may experience reduced communication space along with auditory masking in the presence of anthropogenic noise (Clark et al. 2009; Erbe et al. 2016). Additionally, the noise can cause alterations in pinnipeds' behaviour. Behavioural reactions of seals to the continuous noise have been the focus of various previous studies. In Koschinski et al. (2003) an experiment with the playback of broadband noise simulating an operational wind generator showed that harbour seals reacted to the noise by increasing their median distance from the sound source when surfacing. Experiments with captive harbour seals (Kastelein et al. 2006) revealed the discomfort Sound Pressure Level (SPL) threshold to be approximately 107 dB for different types of high-frequency acoustic stimuli, both transient and continuous. Aversiveness experiments with grey and harbour seals being exposed to different stimuli, including 500 Hz sine wave, predicted an avoidance threshold of 144 dB. This sound level triggered the response of moving away from the sound source (Götz and Janik 2010). It was also noted that the strongest reaction was always observed during the first trial of each type of stimulus. In an experiment (Sills et al. 2015) where two captive ringed seals were exposed to continuous tonal stimuli, masking thresholds were revealed. It was shown that masking occurred when the critical ratio at 400 Hz reached 20 dB and the masking threshold was 102 dB. The cumulative Sound Exposure Level (cSEL) of free-ranging tagged seals exposed to the ship noise was studied in Jones et al. (2017), Chen et al. (2017). Behavioural responses of free-ranging grey and harbour seals to shipping noise were investigated by Mikkelsen et al. (2019a). In this study, seal tags were equipped with 3D accelerometers and sound sensors. At the approach of a ship, a grey seal was shown to suddenly terminate its ascending dive prior to completing the surfacing. On another encounter with a ship, a harbour seal was observed to escape from the sound source by diving deeper and staying in deeper water for a bit longer before the sound pressure dropped. An overview of studies on the disturbance behaviour of seals exposed to continuous noise is given in Table 1. It can be seen that the numerical estimates for the SPLs that cause the onset of biologically significant adverse effects, such as the onset of behavioural reactions of seals, are still lacking.

The focus of the study is on the impact of low-frequency continuous noise radiated by ships on seals. Shipborne underwater noise is radiated by an ensemble of distributed acoustic sources, with the largest contribution coming from propeller cavitation. In the farfield, a ship is commonly considered a point source with a frequency dependent source level (SL). Although an actual SL of a ship is direction dependent, this dependence is usually neglected for the sake of simplicity and ships are modelled as omnidirectional sources located at the ship's acoustic centre. In modelling ship-radiated underwater sound, it is necessary to know the source spectrum of individual ships. For this, parametric formulas such as the RANDI model (Breeding et al. 1994) are widely used. Ideally, instead of using the formulas, the source spectrum should be measured. According to the standards (ISO 17208-2.2:2019), precise measurements of a ship's source spectrum require specific conditions to be satisfied, such as a greater depth at the measurement site. When the SL of the ship and its location are determined, it is possible to model sound propagation and assess the sound exposure of seals in the proximity of the ship. Once the snapshot of the sound propagation is known together with the location of the tagged seal, it is possible to assess its sound exposure and behavioural impairment by the analysis of dive profiles. The main purpose of this study is to estimate the SPL radiated by a ferry, causing the onset of behavioural reactions that can be seen as irregularities in the dive profiles of seals at the close approach of the vessel.

2. MATERIALS AND METHODS

2.1. The study area

The study area is located in the Suur väin (Suur Strait), which lies between Muhu Island and the mainland (Fig. 1) and is crossed by the busy Virtsu–Kuivastu ferry route. The distance between Virtsu and Kuivastu is around 7 km. Other shipping lanes in the study area have significantly less traffic and are therefore not addressed in this study. The water depth in the area is very shallow, with a maximum depth not exceeding 20 m.

2.2. Handling of animals, tagging devices and data processing

Three adult ringed seals were caught for tagging with custom-designed tangle nets set in proximity to the seal haul-outs in the Väinameri on May 21, 2009. The entangled seals were restrained for tagging for the shortest possible time. A telemetry tag (GPS phone tag, Sea Mammal Research Unit (SMRU), St Andrews, UK) was attached to the fur in the upper neck area using quick-setting epoxy resin. The telemetry tag registers the seal's geolocation in 20-minute increments using onboard Fastloc® GPS. The dive depth was measured by an ambient seawater pressure sensor that has a 0.1 metre resolution. The dive detection threshold of the device was set at 1.5 metres for differentiating between surface activities, wave action and diving to depth. Dive profiles were calculated for each dive by an onboard algorithm that uses 9 intermediate depth points selected and saved from the continuous measurement at the end of the dive (McConnell et al. 2004). The end date for all tags was April 20, 2010 without retrieval. However, shorter period recordings of seals' geolocations were identified, with none of them covering the breeding period, which usually takes place between February and March (Helle 1983). Due to the seals being adults, it can be assumed that they have had previous experience of encountering ferries and their reactions are not naive reactions to a new factor. The tagged ringed seals were further identified as A1, A2 and A3. The recording periods for all GPS phone tags are presented in Table 2.

2.3. SL estimation of the ferries and sound propagation modelling

During the observation period, the ferry route between Virtsu (mainland) and Kuivastu (Muhu Island) was serviced by three ferries: the M/S Regula (Fig. 2), the Scania and the Viire. The length of the M/S Regula is 71.2 m and its average crossing speed around 9–10 knots. The M/S Regula has the capacity of 400 passengers and 105 ve-

Table 1. Overview of studies on disturbance reactions of phocids to continuous underwater noise

Seal species	Type	Signal type	Freq. (kHz)	BHT (dB)	Observed reactions	Reference
Harbour	W	Continuous BB, peak source levels of 128 dB (re. 1 µPa2 Hz–1 at 1 m) at 80 and 160 Hz TOB	0.02–8	None	Increasing the median distance to the sound source when surfacing	Koschinski et al. 2003
Harbour	C	Continuous	24	107	Seals moved to areas with tolerable sound levels	Kastelein et al. 2006
Grey and harbour	C, W	Continuous 6s bursts, tonal and square	0.5	135–144	In captivity: turning away, flight and avoidance of catching fish at the first signal. In wild: deterrence effect on the seals	Götz and Janik 2010
Ringed	C	Continuous, tonal	0.1–72.4	97–102 dB @ 400Hz	Masked threshold	Sills et al. 2015
Grey and harbour	W	Ship noise	BB	None	Predicted mean cSEL for 24 hours	Jones et al. 2017
Grey	W	Ship noise	BB	None	Predicted mean cSEL at observed distance	Chen et al. 2017
Grey and harbour	W	Ship noise	0.1–50	113	Interrupted ascent before returning to the surface to breathe	Mikkelsen et al. 2019a

BHT – Behavioural hearing threshold (ISO 18405:2017), C – in captivity, TOB – 1/3 octave band, W – in wild, BB – broadband.

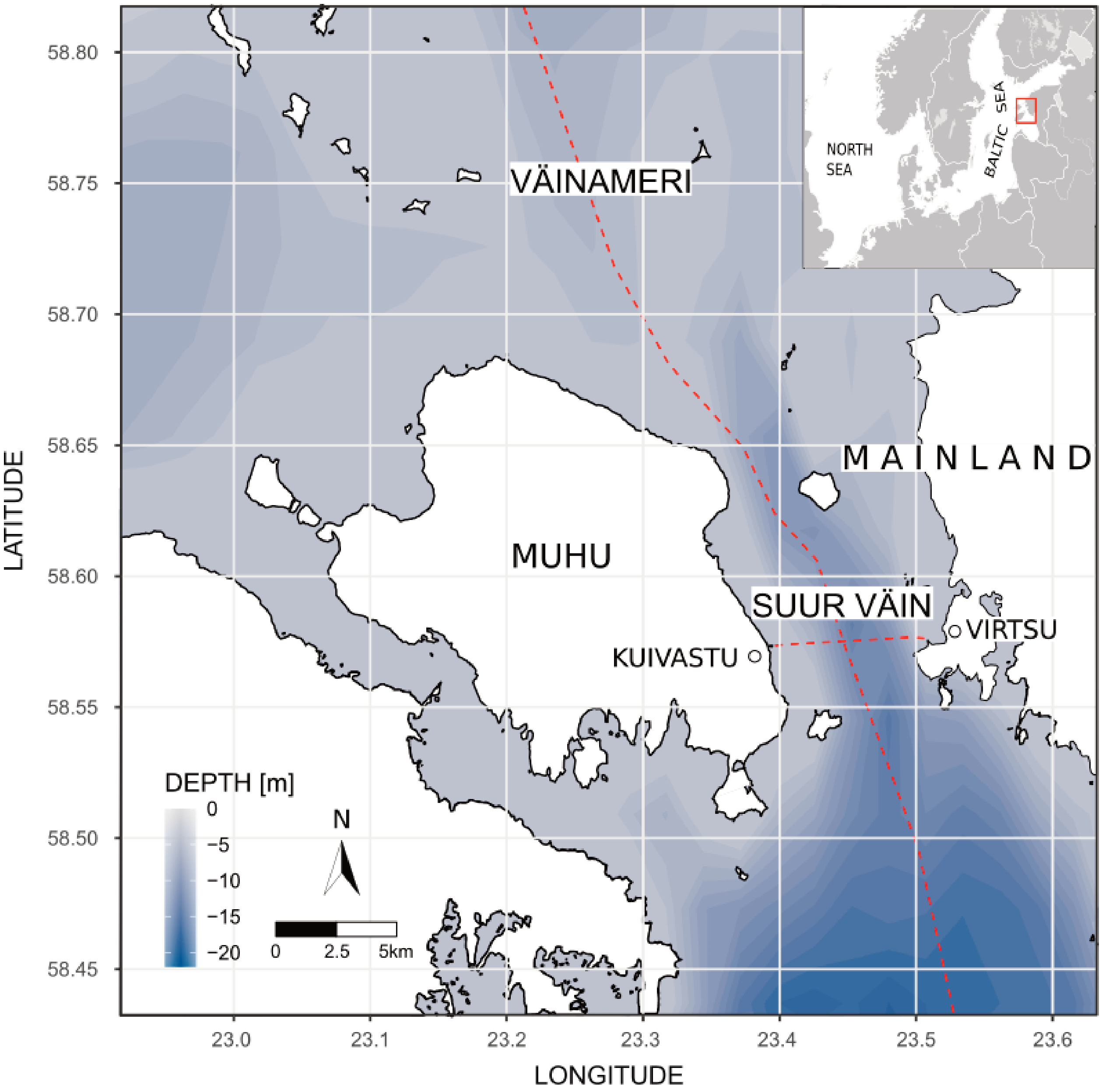

Fig. 1. Map of the study area in the Suur väin, Estonia. The red dashed lines indicate the main shipping lanes.

hicles. Two ferries are often scheduled to depart from two opposite ports at the same time. There are 24–30 crossings in each direction, with the time intervals between crossings varying from 5 hours at night to 35 minutes during the rush hour.

In June 2018, the underwater sound radiated from the M/S Regula was measured. The measurement was made with a GeoSpectrum M36 hydrophone that was submerged to a depth of 5 metres in a 15 m deep water column. The closest point of approach (CPA) during the recording was 800 m. The measured SPLs were calculated with an averaging time of 9 s in TOBs (Fig. 3).

To assess the SL of the ferry, propagation losses between the ferry and the hydrophone have to be estimated. For an isovelocity waveguide with a constant depth, the transmission loss (TL) can be approximated with the equation

$$TL = 20 \log_{10}(H/1m) + 10 \log_{10}[(R–H)/H], \qquad (1)$$

Table 2. Recording periods of three GPS phone tags

ID	Deployment date	Recording periods			
		Start	End	Duration (days)	End date
A1	2009-05-21	2009-05-29	2009-10-19	143	2010-04-20
A2		2009-05-31	2010-01-05	219	
A3		2009-05-23	2009-09-11	111	

Fig. 2. Vessel M/S Regula, whose SL was estimated based on the measured sound signals recorded when it was operating the Virtsu–Kuivastu ferry route.

where H is the depth of the water column and R denotes the range to the source. This equation assumes spherical spreading when the distance from the source is less than H metres, and cylindrical spreading from that time onwards. Inserting in Eq.(1) the depth H = 15 m and the range R = 800 m, the TL = 41 dB. Figure 4 shows the calculated SL of the ferry in octave bands.

For comparison, the SL of the ferry was calculated using the RANDI model (Audoly et al. 2014). The estimates of the RANDI model coincide reasonably well with the measurement based estimates. As the other ferries have similar lengths and cruise speeds, the RANDI model was also used for the SL estimation of the other two operating ferries. The measured data and the RANDI model SL estimates in the broadband (10 to 2000 Hz) are 171 and 169 dB re. 1µPa @1m, respectively.

In the study, sound propagation was modelled using Quonops Online Services (Guelton et al. 2013). The analysed frequency band was chosen based on the existence of strong low-frequency sound attenuation in shallow water, which significantly affects the received spectra levels of the ship noise (Jensen et al. 2011).

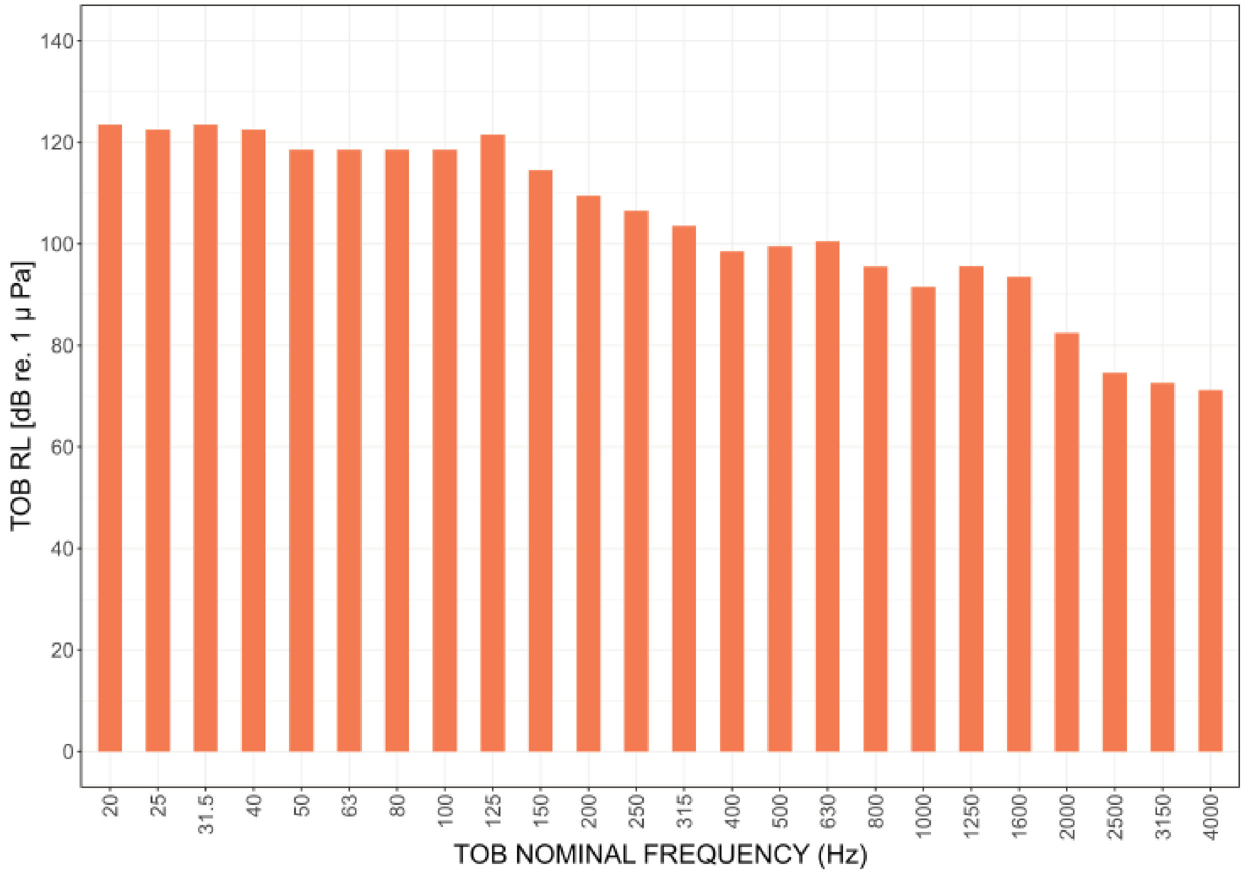

Fig. 3. Measured TOBs of the RLs of the M/S Regula. The averaging time for the level calculation was 9 s and the recording was made at the ship's closest approach to the hydrophone (800 m).

Moreover, seals are known to be more sensitive to high-frequency sound. For these reasons, sound propagation was modelled at 500 Hz TOB (Prawirasasra et al. 2021), which propagates relatively well in the study area while having the potential to disturb the seals.

2.4. Dive profiles

Patterns in dive profiles when crossing the Suur väin were studied using a subset of the ringed seals' tracking data in an area extending 1.5 km to the north and south of the ferry route. The behavioural reactions of seals were considered to be apparent changes in dive profiles, average speeds and movement directions during the closest approach of a ship. The distances between the ships and seals were estimated using the Automatic Identification System (AIS) ship location reports and the tracking data of individual seals. The AIS reports provide information about ship type, name, MMSI numbers identifying vessels, geographical location, speed over ground, etc. Reports are broadcast by vessels equipped with AIS transponders.

Behavioural responses of transiting seals were studied by visually comparing their dive profiles with predefined "normal" dive profiles with regular dive intervals. Uncommon dive patterns in proximity to a ship might indicate a behavioural response. Disruption in dive profiles can manifest as prolonged/reduced duration of diving/surfacing or increased dive depth (Mikkelsen et al. 2019a). In addition, changes in the direction of movement away from the source of the noise were studied. Avoidance reactions can be quantified through drastic changes either in travelling directions or swimming speeds. However, it should be noted that the tracking data contains only the averaged speed values between two consecutive surfacings and therefore acute reactions are unlikely to be detected from this data.

3. RESULTS

3.1. Tracking data analysis

In total, the three tagged ringed seals crossed the ferry route 36 times during the monitoring period. The north-

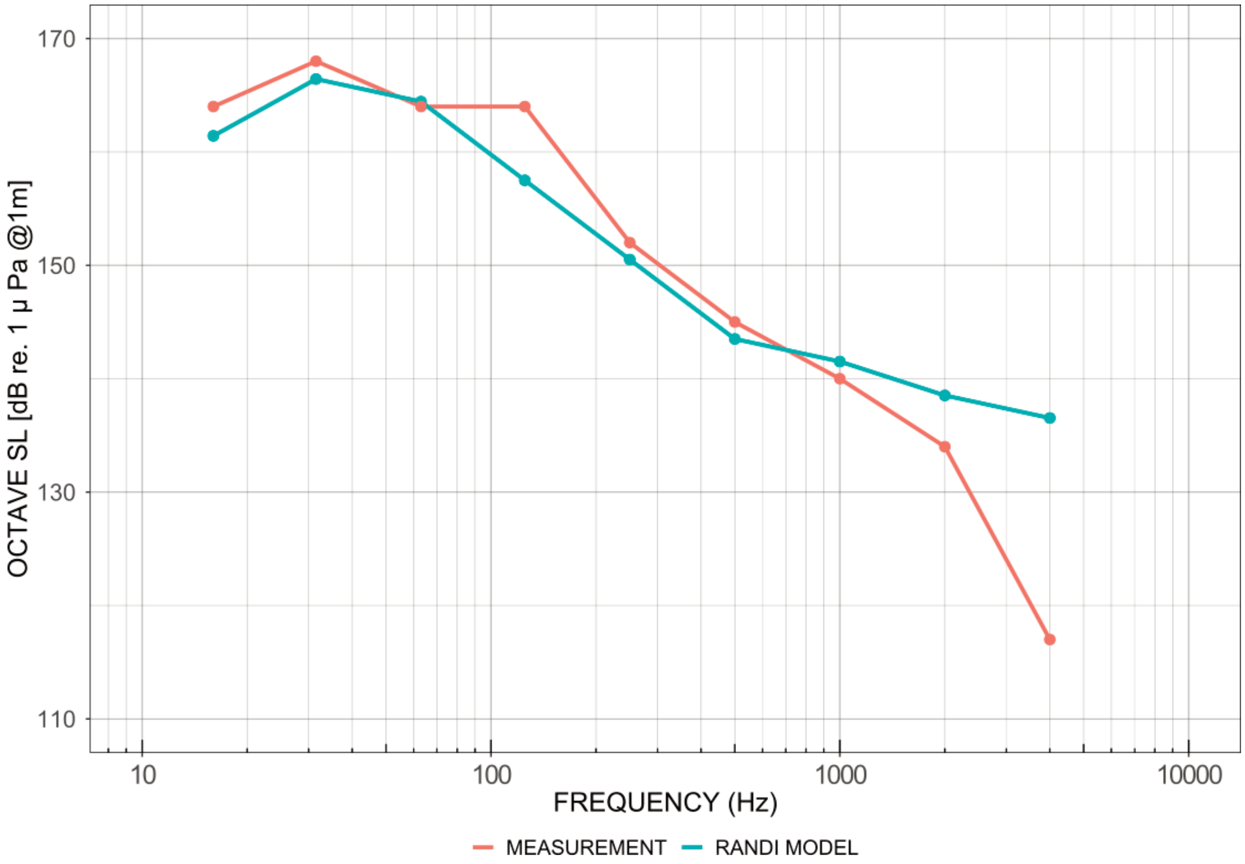

Fig. 4. Estimated octave band SLs of the M/S Regula based on the measurement (red line) and the RANDI model (blue line).

south transit of the seals can be represented through a time series of latitudes (Fig. 5). The prevalent latitude 58.7° corresponds to the haul-outs in the Väinameri and the latitude 57.5° to the foraging areas in the southern part of the Gulf of Riga (Fig. 6). Active foraging periods during the summer months from June to August can be noted when the seals spent longer periods of time at southern latitudes. In autumn the animals spent more time in the haul-outs on small islets at northern latitudes (Halkka and Tolvanen 2017).

The trajectories of individual seals give an overview of their transiting routes (Fig. 6). The three seals displayed individual rather than group behaviour. The trajectories also show that the Suur väin is a vital area for the transit of ringed seals. Most of the ringed seals' crossings occurred during the day when ferries were operating.

The seals passed through different parts of the Suur väin on the ferry route. For simplicity, the strait was subdivided into three transit zones along its width: two coastal zones (i and iii) and a central zone (ii) (Fig. 7). The number of passages through these zones in two directions was 16 for zone i, 18 for zone ii and 2 for zone iii.

3.2. Dive profile patterns of ringed seals

Analysis of the tracking and AIS data showed that in 22 out of 36 passages the closest distance between the tagged seal and the ferry exceeded 500 m. It was also verified that no other ships were in the vicinity at the time of these crossings. Assuming that the noise of distant vessels in this shallow sea is negligible, the shapes of dive profiles for these 22 passages can be considered as unaffected by the ship noise. The most common unaffected dive profile was U-shape, followed by the less common V-shape and the least common "square wave" shape.

The unperturbed profiles can be characterised by dives and surfacings at regular intervals (Fig. 8). The seals continued underwater for 239 ± 49 s before taking breath by remaining above the sea surface for 31 ± 6 s. The dive depth variations demonstrate that seals usually dive relatively close to the sea bottom (Crawford et al. 2019). This pattern of regular dives lasting around 3–5 min with short surfacings is typical of transiting animals (Kelly and Wartzok 1996).

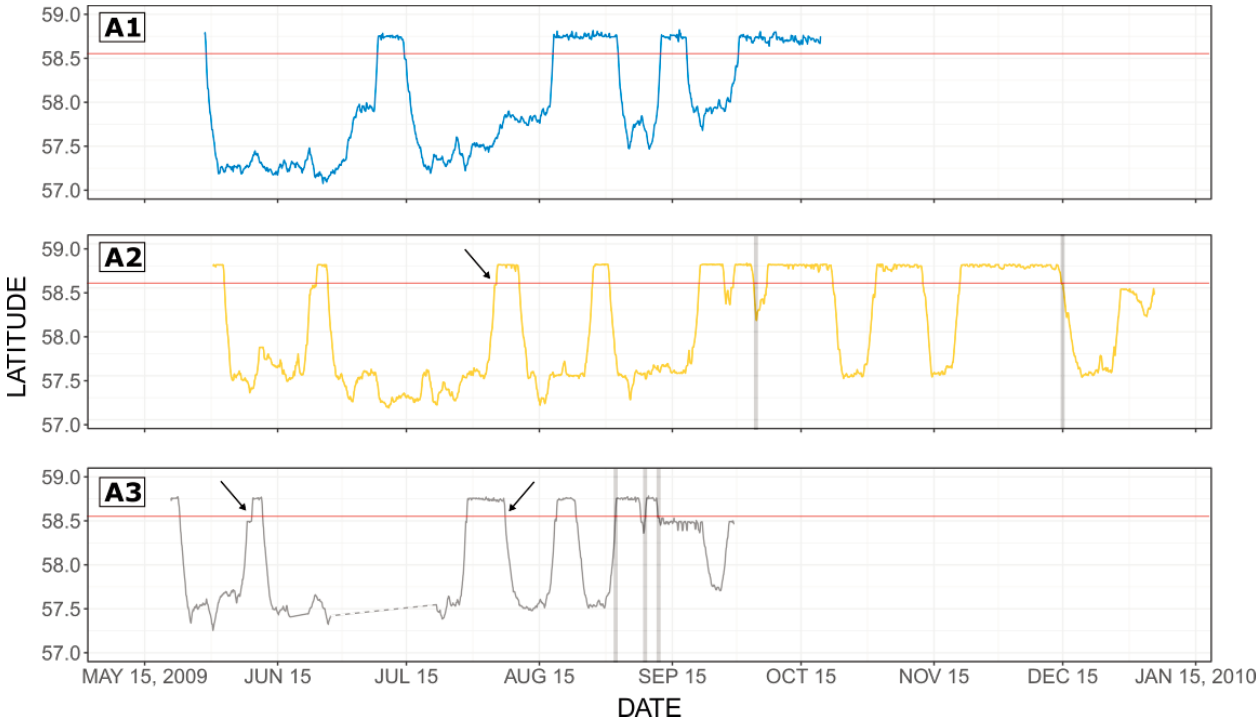

Fig. 5. Time series of the latitudes of the three transiting seals A1, A2 and A3. The horizontal red lines signify the latitude of the ferry route. The vertical grey bars indicate crossings made during night. Close encounters of seals with ferries are shown by arrows. The period of the transmission interruption is indicated by the dashed line.

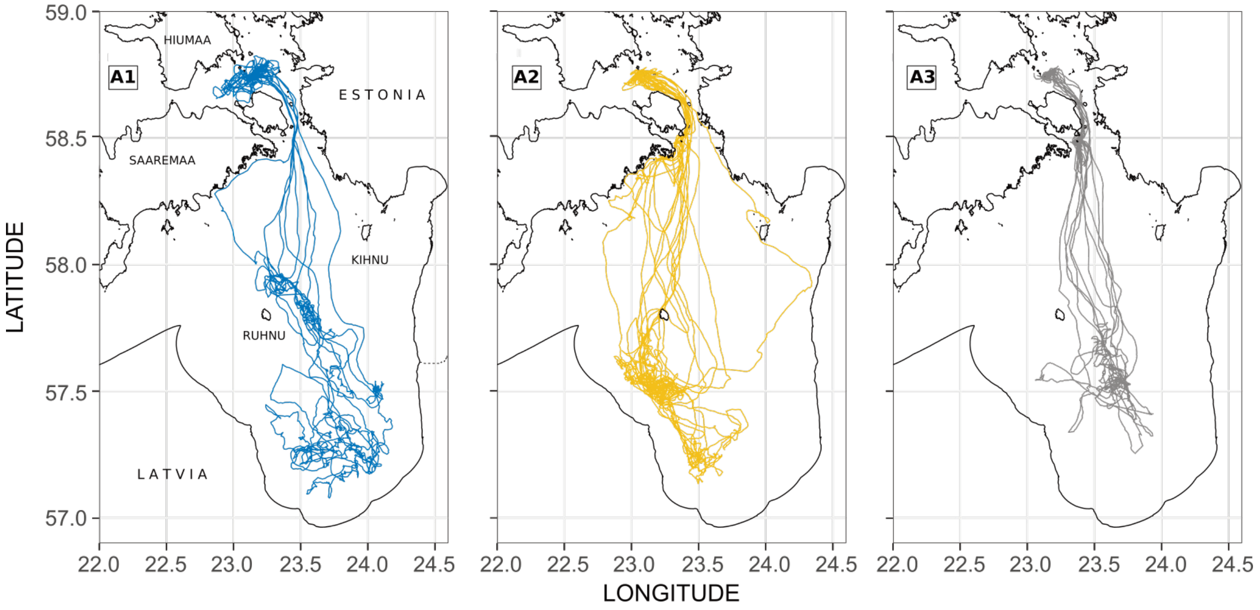

Fig. 6. Trajectories of three transiting ringed seals A1, A2 and A3 throughout the monitoring period. Blue, yellow and grey colours represent A1, A2 and A3, respectively.

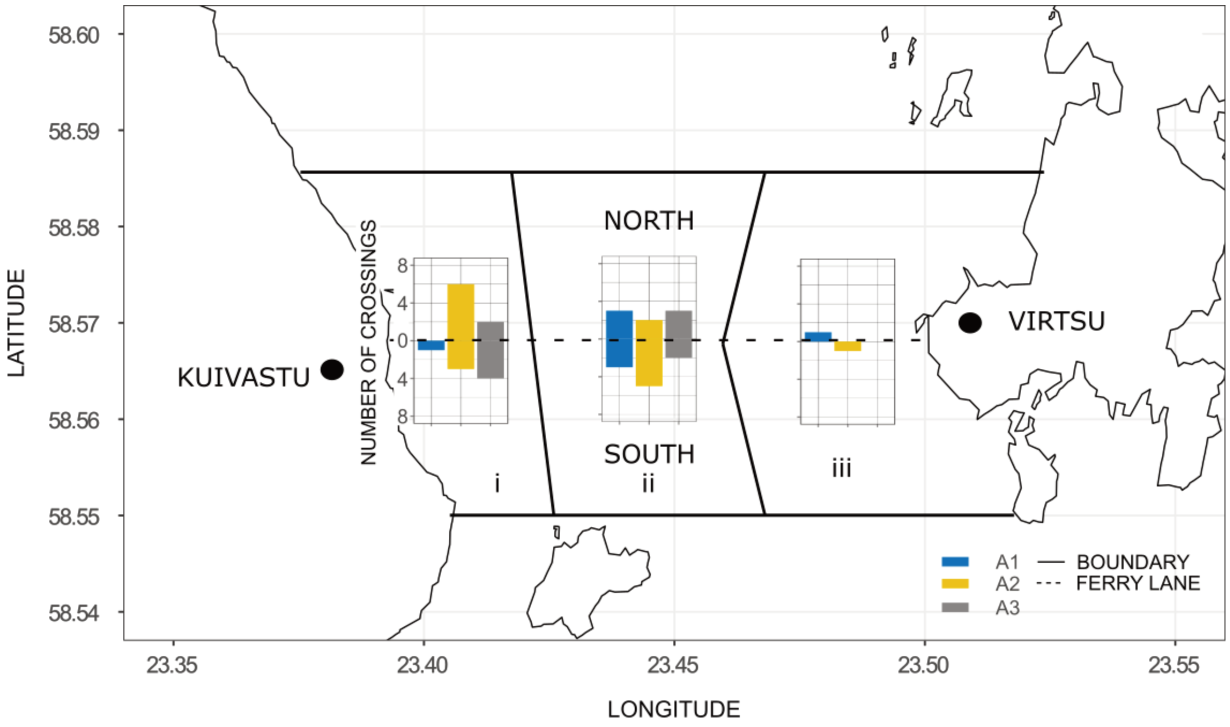

Fig. 7. Bar plots showing the number of ferry route crossings by the seals in three transit zones of the Suur väin. The labels on the bar plots indicate the direction of transiting. The colours blue, yellow and grey on the bar plots signify the passages of the individual seals A1, A2 and A3, respectively. i, ii, iii refer to three transit zones in the Suur väin.

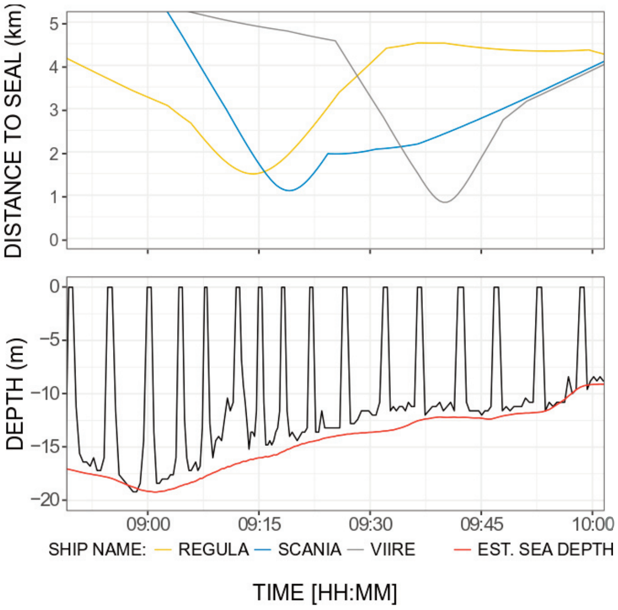

Fig. 8. Typical regular dive pattern of a seal at a great distance from the ship. In this example the M/S Viire was more than 900 m away from the seal crossing the Suur väin through zone ii. The location of the transit zone can be seen at Fig. 7.

3.3. Behavioural reactions

Three dive profiles were found corresponding to very close ferry encounters with two different CPAs: twice at 35 m and once at 50 m. Two of the profiles demonstrated possible reactions of ringed seals to the ship noise. For all close encounters, the speed of the ferries and consequently the SL was almost the same. The dive profiles in question are depicted in Fig. 9 together with graphs showing the distances to the ship.

When comparing dive profiles before and after a close encounter with the M/S Regula, seal A3 dived regularly without showing notable changes at a distance of 50 m from the vessel (Fig. 9A). In another occasion (Fig. 9B), seal A2 made a longer surfacing, then a short dive, followed by short surfacing. At the moment of the closest approach of the ship at 35 m, the seal made a deep dive, which can be considered as a possible behavioural reaction to the ship-radiated noise. Deep diving is known as one of seals' natural reactions to danger, and thus with some reservations the latter dive can be interpreted as a sign of behavioural reaction.

A more pronounced reaction of seal A3 was observed during the closest approach of the ship at 35 m (Fig. 9C). The seal's dive profile remained regular while the ferry

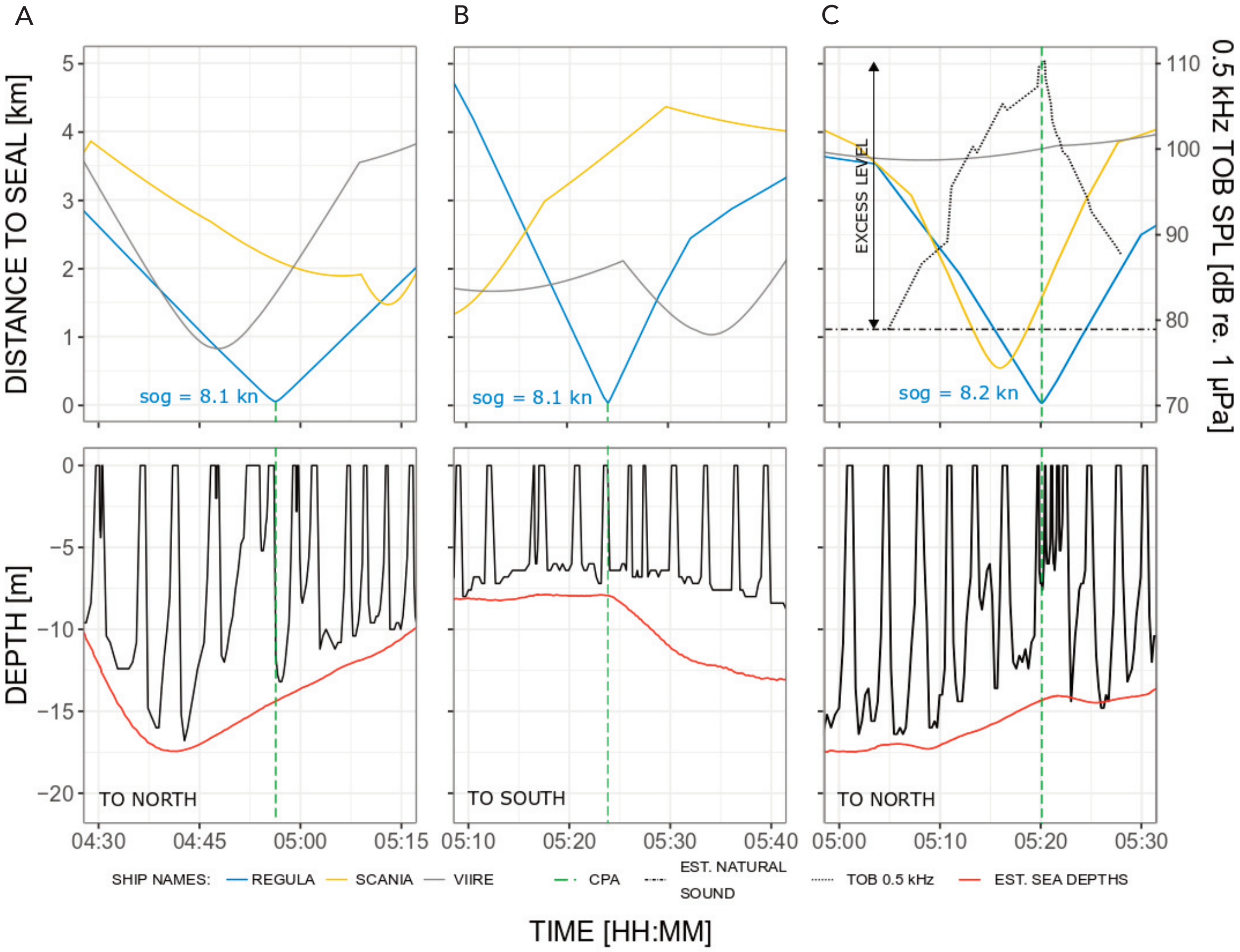

Fig. 9. Seal dive profiles at the close approach of the ship. The upper diagrams show the seal's distance to the ship as a function of time. The CPAs correspond to seal A3 at 50 m (A) and seal A2 at 35 m (B). C shows drastic changes in the dive profile of seal A3 during the approach of the M/S Regula at a CPA distance of 35 m. The dashed green lines indicate the times of the CPAs. The modelled SPL at the location of the seals is shown by the black dotted line. The natural ambient sound level is shown by the horizontal dash-dot line and the excess level by the arrowed line. The sailing speeds of the M/S Regula at the CPAs are expressed in speed over ground (sog) as shown by labels.

Scania passed the seal at 500 m. However, when the second ferry M/S Regula passed at 35 m, there were apparent changes in the form of subsequent surfacings and short dives. The surfacing duration dropped significantly to 4–12 s compared to the usual 31 s. Also, the duration of dives was drastically reduced from the usual 239 ± 49 s to 32–48 s. This different pattern was observable for 152 s and it was initiated 26 s before the CPA. The RL at the location of potential seals was estimated by modelling to be 110 dB at 500 Hz TOB. This SPL value can be assumed as a proxy for the BHT of ringed seals. Considering the average modelled natural ambient SPL in the area to be 80 dB, the behavioural reaction occurred at the excess of the anthropogenic sound by 30 dB.

DISCUSSION

In the present study we have focused on the analysis of the seal dive profiles and the assessment of the ship-radiated SPL with the help of sound propagation modelling. Based on the analysis of the close encounters between the seals and the ships, we have found at least two cases out of 36 crossings where irregularities in the dive profiles occurred, which could indicate a reaction of the seals to the ship noise. In the first case, the reaction of an irregular deep dive was observed and in the second case, there were multiple surfacings of very short duration. It is known that seals can surface in response to loud underwater anthropogenic noise (Sills et al. 2015). The onset of the surfacing reaction was only 26 s before the CPA and can be explained by the actual directivity of the ship-radiated sound. It is known that the sound radiating from the stern can have a higher radiated sound level (Gaggero et al. 2013; Klauson and Mustonen 2017) compared to the bow direction.

Besides the changes in the dive profiles, the seals' direction of travel and swimming speed did not reveal any significant changes during the passage of the ship. This can be attributed to the adult seal's habituation to the ship traffic, as well as to the insufficient resolution of the data, where only the average speed is recorded and sudden acute changes are averaged out.

As for the BHT that we assessed, its value of 110 dB at 500 Hz TOB can be compared to that of Mikkelsen et al. (2019b), where the seal reacted to 113 dB BB noise, which corresponds to 92 dB at 500 Hz TOB. Another comparable BHT can be found in Kastelein et al. (2006), where seals reacted to sound at a level of 107 dB, although the stimuli in this study had the frequency of 24 kHz. Our BHT values are considerably lower than those predicted by Götz and Janik (2010), but in our case the observed reactions were probably much less pronounced than the flight reactions in the referenced study. The responses observed in the present study match the low severity response (1) on the severity scale of behavioural responses in Southall et al. (2021).

CONCLUSIONS

Transiting of three ringed seals was monitored using telemetry tags. Analysis of the tracking data showed that the seals regularly transit between the haul-outs in the Väinameri and the foraging areas in the southern part of the Gulf of Riga. The seals passed through the Suur väin at least twice a month. Therefore, the Suur väin can be considered an important transit area for ringed seals. The ferry route between Virtsu and Kuivastu crosses the Suur väin and is the largest contributor of underwater anthropogenic noise in the area.

The analysis of the seals' movements did not reveal any evidence of strong avoidance reactions in response to the ship noise. At the approach of the ships, the seals did not change either their swimming direction or speed, thus showing habituation to the ship traffic. However, the data on the speed of the seals might have been incomplete, as the telemetry tags used reported only the average speed calculated from the known surfacing locations of the animals.

Owing to the relatively low shipping density, underwater noise radiated from ferries seems to have a low impact on transiting seals. Based on the tracking information from the three tagged seals, exposure to the higher levels of radiated noise could occur during two crossings out of 36, both demonstrating possible disturbance behaviour of the dive profiles. In one case, when the seal was 35 m from the ferry, pronounced disruptions to regular dive patterns were identified. The modelled reception level of the seal was 110 dB at 500 Hz TOB at the closest approach of the ship. Based on the two above-mentioned cases, the BHT was estimated. It should be noted that the comprehensiveness of the results is limited by the small number of cases available for this study. However, the obtained results are quite close to those known from the literature. Based on the results of this study, it can be suggested that due to the relatively short exposure time, the seals' energy budget is unlikely to be compromised by ship-radiated underwater noise from the ferry lane.

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Parvlaevateede allveemüra mõju rändavate Läänemere viigerhüljeste sukeldumisharjumustele

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Mõistmaks inimtekkelise allveemüra mõju mere-elustikule, on oluline koguda andmeid erinevate mereliikide käitumuslike reaktsioonide ilmnemise kohta. Kolme vabalt liikuva viigerhülge (*Phoca hispida botnica*) liikumisi jälgiti neile paigaldatud andmesalvestite abil. Andmed näitasid, et viigerhülged ujusid korduvalt Väinameres asuvate lesilate ja Liivi lahe lõunaosas paiknevate toitumisalade vahel. Seetõttu peavad nad oma liikumisteel ületama Virtsu-Kuivastu parvlaevade trassi, mille käigus võivad hülged sattuda laevadelt tuleneva allveemüra levipiirkonda.

Viigerhüljeste sukeldumismustritest otsiti laevade kiiratud mürast põhjustatud käitumisreaktsioone. Töö tulemusena märgati osas neist ebakorrapärasusi, mis avaldusid sügavate sukeldumiste või korduvate pinnale tulekutena. Viigerhüljeste käitumises häiringu tekitanud registreeritud helitaset hinnati helilevi modelleerimise abil. Saadud tulemused langevad üldjoontes kokku eelnevate vabas looduses ja tehisoludes olevate hüljeste uuringutulemustega. Võib väita, et töös vaadeldud käitumuslikud reaktsioonid ei oma lühikese kokkupuuteaja tõttu pöördumatut mõju viigerhüljeste energiabilansile.