Vessel Noise Exposures of Harbor Seals Tagged in the Elbe Estuary

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Contents

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Abstract

Harbor seals are top marine predators in the North Sea and neighboring estuaries, including the Elbe. The Elbe estuary is a major shipping corridor, with ~7000 vessels, including cargo ships, tankers, and cruise liners, arriving and departing Germany's Hamburg Port annually—Europe's third largest port. To investigate the potential impacts of shipping noise on marine wildlife, eight harbor seals were captured in the Elbe and equipped with sound and movement tags (DTAGs) to measure fine-scale movements and vessel noise exposure. From over 1200 hours of underwater recordings, 574 ship passages were identified with received sound pressure levels >97 dB re 1 μPa in the 2 kHz decidecade band and signal-to-noise ratios >6 dB above ambient. Four seals remained in the estuary throughout the deployment, while others transited into the Wadden Sea and/or North Sea. Daily vessel exposure rates varied among individuals, depending on habitat use rather than tagging location, with estuarine seals experiencing up to 55 high-amplitude vessel passes per day—an order of magnitude higher than rates recorded on seals from the Wadden Sea. As harbor seals are known to respond to vessel noise, further analyses will evaluate behavioral and energetic consequences of vessel exposures in the Elbe estuary.

Keywords

Underwater radiated noise · Anthropogenic noise pollution · *Phoca vitulina* · Pinnipeds · Marine mammals · Biologging · On-animal sound recordings

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Introduction

Underwater soundscapes have undergone significant transformation since the Industrial Revolution, primarily due to the intensification of human maritime activities. Commercial shipping, passenger transport, and offshore industries now dominate many coastal regions, making vessel noise a persistent and ubiquitous feature of the Anthropocene Ocean (Duarte et al. 2021). With further growth of maritime sectors, underwater noise levels are expected to continue rising (Jouffray et al. 2020).

Harbor seals (*Phoca vitulina*) occupy coastal and estuarine habitats where they rely heavily on acoustic cues for communication, predator detection, and foraging (Hanke and Reichmuth 2022). Their best underwater hearing ranges from approximately 500 Hz to 40 kHz (Kastelein et al. 2009), which overlaps with many anthropogenic noise sources, including shipping. Consequently, harbor seals are at increasing risk of vessel noise-induced impacts, such as behavioral disruption, auditory masking, and elevated physiological stress. If experienced repeatedly and over prolonged periods, these impacts may result in energetic imbalances and consequences at the population level.

The North Sea, a critical habitat for harbor seals, is one of the most acoustically polluted marine environments globally due to dense shipping lanes, commercial fisheries, and the expansion of offshore energy infrastructure (Emeis et al. 2015; Duarte et al. 2021). As a result, vessel noise is expected to be a major contributor to the soundscape experienced by seals inhabiting this region (Kinneging et al. 2023). Assessing seal exposure to vessel noise is therefore important for informing mitigation strategies and conservation efforts. Current approaches often rely on AIS data and sound propagation models (e.g., Jones et al. 2017), but these can underestimate actual noise levels because they exclude non-AIS vessels, which can be particularly error-prone in estuarine environments dominated by small-size recreational boat traffic (Haviland-Howell et al. 2007; Jones et al. 2018). Direct on-animal recordings therefore provide a more accurate representation of noise exposure.

Sound and movement tags (DTAGs) equipped with hydrophones and high-resolution motion sensors have been used to directly monitor seal behavior and anthropogenic noise exposure (Mikkelsen et al. 2019). Using this technology, a previous study documented anecdotal behavioral responses to ship noise, including interruption to resting at the sea floor and changes in diving patterns (Mikkelsen et al. 2019). A subsequent study in the German Wadden Sea systematically quantified vessel noise exposures from DTAG deployments, revealing that tagged seals were repeatedly exposed to high-amplitude vessel passes, 4.3 ± 1.6 times per day while at sea, even in designated marine-protected areas (Nachtsheim et al. 2023). Moreover, changes in behavioral states of harbor seals were reported in response to increasing ambient noise levels, likely driven by vessel noise (Maurer et al. 2025).

The present study was conducted as part of the European Union Horizon 2020 research project "SATURN" (https://www.saturnh2020.eu/), which aims to develop solutions to reduce underwater radiated noise. A central theme in SATURN has been to investigate the impacts of underwater radiated noise from shipping on the behavior, health, energetics, and population dynamics of aquatic organisms

(Schnitzler et al. 2024). One case study focused on the Elbe estuary, one of the busiest shipping lanes in Europe, but also represents an estuarine ecosystem with a year-round presence of harbor seals (van Neer et al. 2023). Harbor seals in the Elbe were equipped with DTAGs to quantify individual exposure to vessel noise in comparison to animals from the Wadden Sea. The same established workflow developed in Nachtsheim et al. (2023) was applied to achieve direct comparability and evaluate differences in vessel exposure rates and the received sound levels. This study represents an important first step to evaluate the consequences of vessel noise exposures for harbor seals in this industrialized estuarine ecosystem and inform decision-making processes for underwater radiated noise from shipping.

Methods

Tag Deployments and Data Processing

Eight adult harbor seals were captured on their haul-out sites in the Elbe estuary during low tide between 2021 and 2023 (see more details in Maurer et al. 2025). While seals were manually restrained, veterinary sampling was conducted for comprehensive investigations on the animals' health status. Prior to release, all seals were equipped with a DTAG-4 (size: 40 × 33 × 180 mm, including flotation, weight: 206 g in air and buoyant in water) by gluing the device on the animal's pelage with a universal instant adhesive (Loctite® 422, Henkel, USA). The DTAG enables high-resolution sound and movement recordings over multiple weeks and was programmed to detach from the animal, by a corroding wire attached to a base plate, after 22 days. Retrieval of the DTAGs was possible due to Argos satellite transmitters embedded in the float (SPOT 6-363; Wildlife Computers, USA).

Each DTAG recorded underwater sound via an onboard hydrophone. Recordings were filtered and stored with a recording bandwidth (−3 dB bandwidth) from 100 Hz to 27 kHz. Sensors were sampled with 200 Hz (acceleration) and 50 Hz (magnetometer and pressure) at 16-bit resolution. The tags also included a snapshot GPS that made 64 ms acquisitions of available GPS satellite signals (Mikkelsen et al. 2019). Raw movement data streams were post hoc calibrated and decimated to 5 Hz using custom MATLAB (R2018b) routines (http://www.animaltags.org).

Fieldwork was approved by and conducted in compliance with animal ethics permits of the German federal states Schleswig Holstein [V312–72241.121-19 (70-6/07), V241-64499/2018 (11-2/19)] and Lower Saxony (33.12-42502-04-17/2562). Additional permits for animal handling and access to the capture sites were provided by the responsible local hunting and nature conservation authorities.

Detection and Classification of Vessel Passes

The detection and classification of vessel noise events from the DTAG sound recordings were conducted as described by Nachtsheim et al. (2023). The processing steps differ from sound recordings made with stationary recorders, as on-animal recordings may contain sounds generated through the movements or vocalizations of the animals. Here, the primary detection metric was the received sound pressure level in the 2 kHz decidecade band, which was selected for its sensitivity to vessel noise and reduced influence from low-frequency flow noise generated by the animals' movements. The following description provides a summary of the workflow.

The continuous sound recordings were divided into 30 s segments, and for each segment, the sound pressure level (SPL) in the 2 kHz band was calculated. A fixed threshold of 97 dB re 1 μPa was established to identify segments with elevated noise levels potentially attributable to passing vessels. This threshold was derived from a receiver operating characteristic analysis of manually labeled data to balance sensitivity and specificity in detecting vessel-related noise events. Any 30 s segment exceeding this threshold was flagged as a potential vessel pass. Consecutive or closely spaced detections (within 5 min) were merged to represent a single event, accounting for the possibility of prolonged or gradual noise increases associated with a vessel's approach or departure.

To ensure reliable detection of vessel passes, background ambient noise levels were estimated using the 25th percentile of the 2 kHz decidecade band levels over 20-min windows with a 10-min overlap. This approach minimized contamination from transient noise sources and allowed the identification of periods with sufficiently low ambient noise levels. Only segments where ambient noise was at least 6 dB below the 97 dB detection threshold were defined as "on-effort," providing sufficient signal-to-noise ratio for accurate identification.

Following automated detection, a manual classification step was conducted to verify the nature of each high-noise event. Each flagged event was independently reviewed by three trained raters using a custom graphical user interface developed in MATLAB. Events were assigned to one of the following categories based on their sound characteristics: "vessel," "potential vessel," "other anthropogenic," "weather/rain," "tag noise," and "unknown." To improve classification accuracy and consistency, only events confidently classified as vessel passes by the raters were retained for further analysis: either all raters classified it as vessel or two raters classified it as a vessel and one as a potential vessel. Agreement between raters was very high, with an overall classification agreement of 93%.

This multistep process ensured robust detection and classification of vessel noise exposures, enabling quantitative assessment of the number of vessel noise exposures and received levels (in the 2 kHz decidecade band) encountered by free-ranging harbor seals in the Elbe estuary.

Results

Spatial Patterns of Seal Movements

Movement patterns of eight harbor seals tagged in the Elbe estuary spanned a large portion of the Elbe River system and adjacent North Sea (Fig. 1). Four individuals remained exclusively within the Elbe estuary throughout their deployments, while

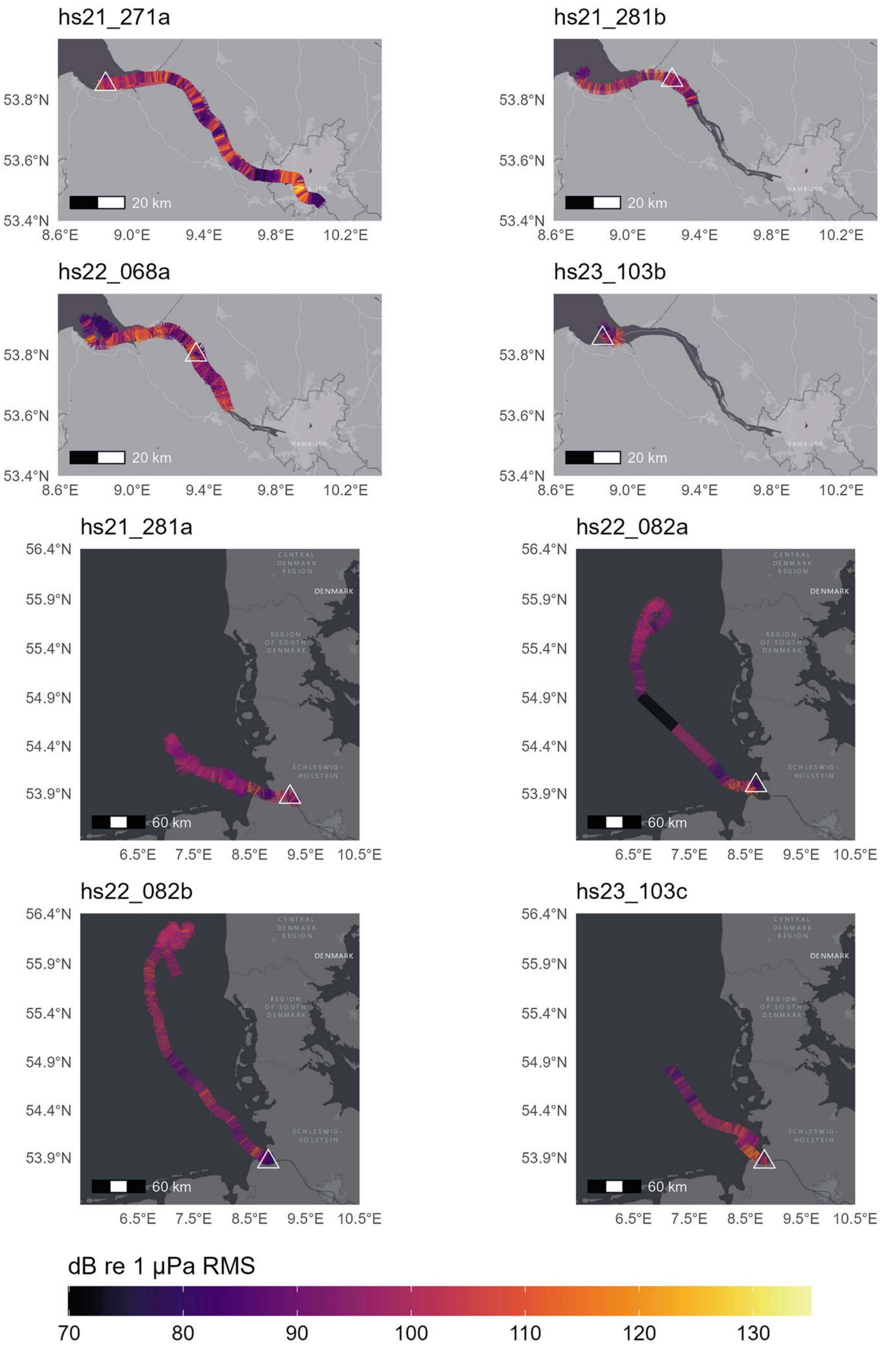

Fig. 1 Individual harbor seal tracks, color-coded by 30-s sound pressure level in the 2 kHz decidecade band (dB re 1 µPa). The white triangle indicates the capture and tagging location in the Elbe estuary. Please note that the extent of the maps varies depending on the area utilized by the seals

the other four moved from the estuary into the Wadden Sea and North Sea for the remainder of the deployment period. This variation in movement provided coverage of both highly industrialized estuarine habitats and more offshore environments, enabling comparisons of vessel noise exposure across contrasting regions.

Exposure to Vessel Passes

Despite being programmed to record for 22 days, tag deployment duration varied between individuals, with some DTAGs recording longer than expected and others detached prematurely (Table 1). The total recording time under water, that is, excluding any haul-out events, surfacing and outage periods, amounted to 1251 hours. The detection and classification of high noise events yielded a total of 1433 vessel passes. Of these, 574 vessel passes occurred during on-effort periods, that is, defined as ambient noise segments >6 dB below the detection threshold of 97 dB (Table 1).

Seals were exposed to a largely varying number of vessel passes per day during on-effort periods (Fig. 2, Table 1). One seal (hs21_281b) in the Elbe estuary experienced the highest vessel exposure rate in this study, with an estimated 54.9 ship encounters per day. The maximum received levels in the 2 kHz decidecade band varied between vessel exposures, with an average SPL of 108 ± 8 dB re 1 μPa and a maximum of 132 dB re 1 μPa (Fig. 2). The duration of the events ranged from 0.5 min and 105.5 min (mean: 5 min).

Table 1 Summary of deployment details and vessel noise exposure metrics for each tagged harbor seal. *Deployment duration* refers to the total time the tag was attached. *Total recording time* represents the effective time when underwater sound levels could be measured, that is, excluding haul-out, surfacing (<1 m depth), and outage periods. *On-effort recording time* includes periods when ambient noise in the 2 kHz decidecade was >6 dB below the detection threshold of 97 dB re 1 μPa. *Number of detected vessels* and *vessel exposure rate* (vessels per 24 hours) were only calculated during on-effort periods

Seal ID	Deployment duration (days)	Total recording time (h)	On-effort recording time (h) (proportion of total recording time in %)	Number of detected vessels on-effort	Vessel exposure rate (number of on-effort vessels/day)
hs21_271a	22.0	169.8	91.3 (53.8%)	357	38.9
hs21_281a	22.0	288.0	114.8 (39.9%)	180	13.0
hs21_281b	4.0	45.4	27.5 (60.6%)	108	54.9
hs22_068a	27.3	232.1	127.9 (55.1%)	585	50.7
hs22_082a	12.5	107.0	31.1 (29.0%)	35	3.9
hs22_082b	26.2	342.9	81.1 (23.7%)	132	5.0
hs23_103b	0.3	3.1	1.8 (58.2%)	8	39.6
hs23_103c	4.4	63.1	29.4 (46.5%)	28	4.9

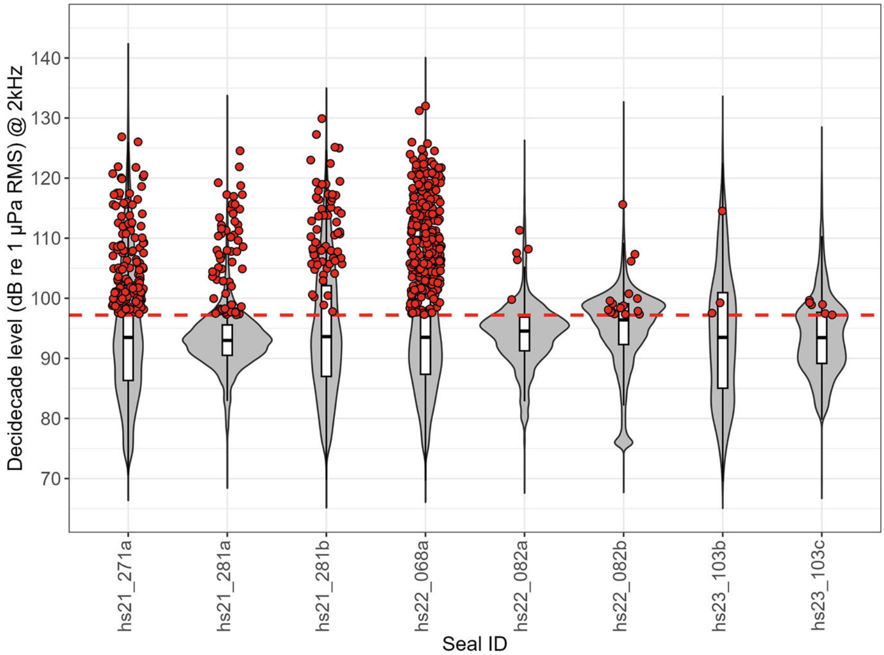

Fig. 2 Distribution of the sound pressure level (SPL) in the 2 kHz decidecade band levels (dB re 1 μPa) over 30 s segments for each seal tagged in the Elbe estuary shown as violin plots. White box plots indicate the median and the interquartile range of each distribution. The red dashed line marks the detection threshold (97 dB re 1 μPa) for the ship noise events. Red dots represent the maximum SPL of individual vessel passes during "on-effort" periods ($n = 574$); the dots are scattered horizontally for better visibility

Spatial Distribution of Vessel Exposures

Four harbor seals remained exclusively in the Elbe estuary, while the other four moved from the Elbe to the adjacent Wadden Sea and North Sea for the remainder of the deployment (Fig. 1). Vessel exposure rates varied largely as a function of habitat choice rather than tagging location (Table 1, Fig. 1). Individuals that stayed mostly in the Elbe estuary (hs21_271a, hs21_281b, hs22_068a, hs23_103b) experienced higher vessel exposure rates (38.9–54.9) compared to those that ventured into the North Sea (3.9–13.0) (Table 1).

Harbor seals from the Elbe estuary were exposed to a highly variable underwater soundscape throughout their deployment (Figs. 1 and 2). The highest received levels were recorded by individuals that ventured into the Port of Hamburg (hs21_271a), whereas received levels were lower in the protected side arms of the Elbe River as well as in certain offshore areas (Fig. 1).

The majority of vessel exposures recorded for tagged seals occurred in the Elbe River and outer estuary, consistent with the elevated received levels observed in these areas (Figs. 1 and 3). In contrast, seals that moved into the North Sea were exposed to fewer vessels (Fig. 3).

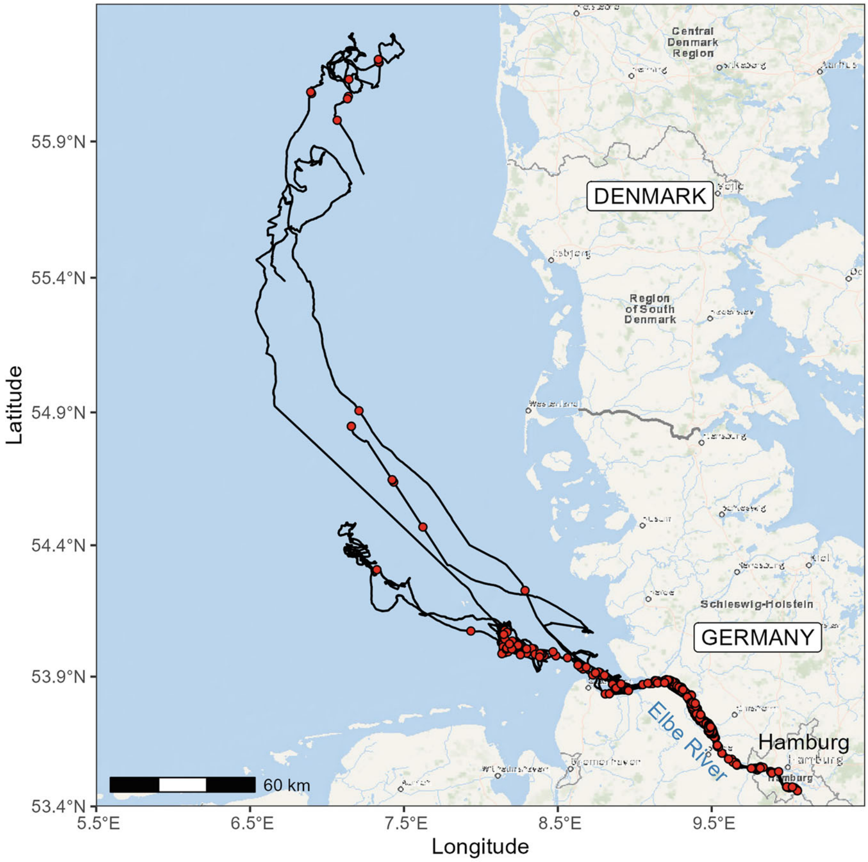

Fig. 3 Tracks of the eight harbor seals tagged along the Elbe River across five capture events over three consecutive years. Tracks span the Elbe estuary and adjacent North Sea. Red dots indicate the locations of high-amplitude vessel passes detected during on-effort periods ($n = 574$)

Discussion

The present study provides a detailed assessment of vessel noise exposures experienced by free-ranging harbor seals in a human-dominated coastal habitat, such as the Elbe estuary. By deploying on-animal sound and movement tags, received levels and exposure events were directly measured, thereby overcoming some of the inherent uncertainties of approaches that rely solely on acoustic modeling and AIS data. The results demonstrate pronounced heterogeneity in exposure rates among individuals, primarily driven by habitat choice, and highlight the elevated exposure risk associated with animals utilizing the heavily industrialized Elbe estuary in contrast to the adjacent Wadden Sea. These findings have important implications for understanding potential behavioral and physiological consequences of vessel noise on pinnipeds, as well as for informing evidence-based management strategies for shipping underwater radiated noise.

Habitat Choice as a Driver of Exposure Heterogeneity

Harbor seals from the Elbe estuary used a wide range of habitats, from the Port of Hamburg to offshore areas in the North Sea. Daily vessel exposure rates varied markedly among individuals, reflecting differences in habitat preferences of individual seals rather than tagging location. Four seals remained within the Elbe estuary throughout the deployment, experiencing 39–55 high-amplitude vessel passes per day, while those that moved into coastal waters of the Wadden Sea and North Sea encountered only 4–13 vessels per day. These exposure rates were found to be comparable to previous deployments on harbor seals from the Wadden Sea (Nachtsheim et al. 2023).

This heterogeneity underscores the importance of considering behavioral ecology when evaluating the risks associated with anthropogenic noise. Seals that selectively use estuarine habitats with major shipping lanes, whether for foraging, transit, or resting, could inherently face more frequent vessel encounters. Conversely, individuals that range more widely into open offshore environments may encounter fewer vessels and experience comparatively quieter soundscapes. Population-level assessments that ignore such heterogeneity risk underestimating noise exposure for high-exposure subgroups within a wider population.

Elevated Exposure Rates in the Elbe Estuary

The Port of Hamburg ranks among Europe's largest ports by annual throughput, transforming the Elbe estuary into a major shipping corridor (Großmann et al. 2007). This intense maritime activity is reflected in the exposure profiles of the estuarine seals. Highest received levels were detected near Hamburg, where cargo ships, tankers, ferries, and cruise liners converge. Animals exploiting the Elbe estuary experienced daily exposure rates an order of magnitude higher than those outside the estuary (Nachtsheim et al. 2023).

This pattern mirrors observations from other urbanized estuarine systems, where shipping lanes, ferry routes, recreational boat traffic, and industrial activity generate quasi-continuous acoustic disturbances (Haviland-Howell et al. 2007; Rountree et al. 2020). For harbor seals in the Elbe estuary, the cumulative exposure levels are particularly concerning, given their relatively small home ranges compared to harbor seals from marine environments (van Neer et al. 2023). Unlike animals that can readily escape localized sources of disturbance by swimming away, estuarine-resident seals may have limited opportunities to avoid high-noise areas due to the geography of the river and the distribution of haul-out sites. Available opportunities include narrow side arms of the river as well as tributaries. As shown in this study, harbor seals may occasionally utilize these acoustic refuges where ambient noise levels are considerably lower, possibly to recover from frequent shipping noise exposures in the main river channel or to search for specific prey.

Potential Consequences of Vessel Noise Exposure

The ecological significance of these exposure patterns lies in their potential to disrupt critical behaviors and impose energetic costs. As harbor seals rely on acute underwater hearing for prey detection, predator awareness, and social communication, high-amplitude vessel noise, particularly when frequent and prolonged, can interfere with these functions through auditory masking (Erbe et al. 2016). Masking may reduce foraging efficiency by obscuring prey cues and thereby interfering with the seals' ability to use passive listening.

In addition to masking, vessel noise may lead to behavioral disturbances. Previous tagging studies on seals have documented avoidance responses, interruptions of resting behavior, and altered dive patterns in response to anthropogenic noise (Mikkelsen et al. 2019; Maurer et al. 2025). Such behavioral changes may not always be substantial but can accumulate over time, leading to increased energy expenditure. For example, interrupted resting at sea can limit recovery from foraging activity, while avoidance responses may necessitate energetically costly movements and missed foraging opportunities.

Energetic consequences are of particular concern for seals in estuarine environments, such as the Elbe estuary, where prey availability may already fluctuate due to natural variability and anthropogenic influences, for example, eutrophication and hydromorphological alterations (Theilen et al. 2025). It has been shown that a seal's foraging decisions are likely driven by behavioral context, prey patch quality, and perceived risk, such as anthropogenic underwater noise, that is, a high risk and poor prey patch quality will decrease foraging success (Hastie et al. 2021). Increased energetic demands for prey search imposed by noise-related disturbances could therefore exacerbate the challenges of fulfilling energetic requirements.

The persistence of harbor seals in noisy estuarine habitats, despite evidence of behavioral disturbance, indicates a complex trade-off between the energetic benefits and the costs of acoustic stress. Such resilience may reflect either high local prey profitability or limited availability of alternative habitats, raising questions about the long-term implications for health, body condition, and reproductive success in chronically disturbed environments.

Management Implications and Recommendations

Given the demonstrated high exposure rates and the potential sensitivity to underwater radiated noise from ships, mitigation strategies should be considered to manage shipping noise. In particular, these approaches should focus on reducing both the intensity and frequency of high-amplitude vessel noise exposures in key seal habitats.

Common mitigation strategies include speed restrictions and re-routing of shipping lanes, both of which represent effective tools in reducing underwater noise emissions from ships in key habitats (Findlay et al. 2023). However, these measures may be difficult to implement in narrow, strong-current riverine systems, such as the Elbe, where maneuverability, water depth, and tidal phase must also be considered, especially for large vessels. Consequently, where slowing down and rerouting shipping activity is not feasible, encouraging or mandating commercial vessels to implement technical solutions (e.g., optimized propeller designs, hull modifications, air injection systems) to reduce underwater radiated noise may be a more promising solution. Technological modifications have been shown to significantly decrease underwater radiated noise from ships (Leaper and Renilson 2012). Implementing relevant measures that reduce underwater radiated noise from commercial vessels particularly when these vessels frequent biologically important coastal environments, such as is the case for the Elbe, could therefore support the mitigation of shipping noise impacts to seals and other marine fauna.

Conclusion

This study demonstrates that harbor seals in the Elbe estuary are subject to high daily vessel noise exposure rates, an order of magnitude greater than those experienced by conspecifics in the Wadden Sea. The heterogeneity in exposure is primarily driven by habitat choice, highlighting the vulnerability of estuarine-resident seals to cumulative anthropogenic noise exposure from shipping. Potential consequences include auditory masking, behavioral disturbances, and increased energetic costs, which may collectively affect individual condition and population dynamics. These impacts deserve particular attention in future studies.

Given the critical ecological role of harbor seals and the importance of the Elbe estuary as both a wildlife habitat and a major shipping corridor, balancing economic activity with biodiversity conservation will require targeted, evidence-based mitigation measures for shipping underwater radiated noise. By implementing speed restrictions, avoiding traffic concentration in haul-out proximity, and encouraging quieting technologies, it may be possible to substantially reduce the acoustic footprint of shipping and safeguard the ecological integrity of this unique estuarine ecosystem.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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