

Similar Hearing Thresholds at 8 kHz, but Dissimilar Susceptibility of Hearing to Damage by 8 kHz Sounds in a Harbor Porpoise, a Harbor Seal, and a California Sea Lion

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Abstract

For each mammalian species, the pattern of susceptibility to temporary hearing threshold shift (TTS) with changing frequency has been assumed to be related to the pattern of hearing thresholds with changing frequency (the basic audiogram). This relationship was tested with one individual of each of three marine mammal species: one odontocete (harbor porpoise [*Phocoena phocoena*]) and two pinniped species (harbor seal [*Phoca vitulina*] and California sea lion [*Zalophus californianus*]). Audiograms showed that they had similar basic hearing thresholds at 8 kHz (61, 59, and 60 dB re 1 μ Pa, respectively). Hearing thresholds for narrow-band sweeps at 11.3 kHz (the hearing frequency at which the greatest TTS occurred in all three species) before and after exposure for 1 h to a continuous, constant-amplitude, one-sixth-octave noise band centered at 8 kHz at several sound exposure levels (SELs) showed that the TTS experienced by the three individuals differed. The 6 dB TTS-onset SELs were for the harbor porpoise: 169 dB re 1 μ Pa²s; for the harbor seal: 182 dB re 1 μ Pa²s; and for the California sea lion: 176 dB re 1 μ Pa²s. The pattern of increase in TTS with increasing SEL was steeper for the harbor porpoise and harbor seal than for the California sea lion. This means that TTS onset occurs at a different sensation level (i.e., at a different number of dB above the basic hearing threshold) in each of the three marine mammal species. Therefore, different policies, recommendations, or regulations for permissible sound exposure are needed for each species.

Key Words: anthropogenic sound, audiogram, criteria, hearing sensitivity, hearing susceptibility, odontocete, otariid, phocid, sound safety levels, temporary threshold shift (TTS)

Introduction

Marine mammals that are exposed to high-amplitude sounds generated by anthropogenic offshore activities, such as dredging, shipping, windfarms, pile driving, seismic surveys, sonar, and detonations, may suffer permanent or temporary hearing threshold shifts (PTS or TTS; Melnick, 1991; Yost, 2007). For the regulation and management of such activities, it is important to know at what sound exposure levels (SELs) hearing sensitivity begins to be reduced in marine mammals (the TTS-onset SEL; see Finneran, 2015). SELs are combinations of received sound pressure level (SPL) and exposure duration that are used to quantify the energy of exposure. Safety recommendations for underwater sound to protect marine mammal hearing were proposed by Southall et al. (2007, 2019) based on the limited TTS data available at the time for each of the “marine mammal hearing groups” (Southall et al., 2019, p. 131) into which the authors divided the species. The weighting functions used to draw up the recommendations were based on one or a few TTS-onset SEL data points per species and on the shape of the basic audiograms; TTS onset was arbitrarily defined as occurring when TTS was > 6 dB (Southall et al., 2007, 2019). Since the publication of the functions, many more TTS data have become available for bottlenose dolphins (*Tursiops truncatus*; Finneran et al., 2023), harbor porpoises (*Phocoena phocoena*; Kastelein et al., 2017a, 2017c, 2019b, 2019c, 2019d, 2020a, 2020b, 2020c, 2021a, 2024a; Schaffeld et al., 2019, 2022), harbor seals (*Phoca vitulina*; Kastelein et al., 2019a, 2019c, 2020d, 2020e, 2020f, 2025a), and California sea lions (*Zalophus californianus*; Kastelein et al., 2021b, 2022a, 2022b, 2024b, 2025b). However, these studies are not all directly comparable because results depend on the environment (background noise

level, reverberance) and audiometric methods used (behavioral or physiological).

The results of basic audiogram and TTS studies conducted by SEAMARCO with three marine mammal species in similar environments, using similar methods, equipment, and data analyses, are directly comparable. The present study compares the unmasked hearing thresholds at 8 kHz and the susceptibility to TTS of a harbor porpoise (Kastelein et al., 2017b, 2024a), a harbor seal (Kastelein et al., 2009a, 2009b, 2025a), and a California sea lion (Kastelein et al., 2022a, 2023). The fatiguing sound frequency of 8 kHz was chosen because the unmasked 50% detection thresholds of the three species for this frequency were within 2 dB of one another. For all three species, the fatiguing sound used was a continuous one-sixth-octave noise band (NB) sound centered at 8 kHz, and susceptibility to TTS was expressed as the lowest SEL at which 6 dB TTS occurred. The goal of the present study was to compare the 6 dB TTS onset and the pattern of increase in TTS with increasing SEL in the three species. Similarity between the species would indicate a common underlying mechanism and a direct relationship between the fatiguing sound's SPL and exposure duration for the three species.

Methods

For full details of the methods, including acoustic equipment used, refer to Kastelein et al. (2009a, 2009b, 2017c, 2022a, 2023, 2024a, 2025a).

Data Sources, Study Area, Ambient Noise, and Terminology

The hearing threshold of harbor porpoise F05 (42 kg; 6 y old) was measured by Kastelein et al. (2017a), and her susceptibility to TTS (49 kg; 11 y old) was measured by Kastelein et al. (2024a). The hearing threshold of harbor seal F02 (~42 kg; 1.5 y old) was measured by Kastelein et al. (2009a, 2009b), and her susceptibility to TTS (~55 kg; 15 y old) was measured by Kastelein et al. (2025a). The hearing threshold of California sea lion F01 (~80 kg; 7 to 11 y old) was measured by Kastelein et al. (2023), and her susceptibility to TTS (70 to 80 kg; 8 to 10 y old) was measured by Kastelein et al. (2022a).

All research was conducted at the SEAMARCO Research Institute in the Netherlands. The harbor porpoise and the harbor seal were kept in pools measuring $8 \times 7 \times 2$ m deep; the California sea lion's pool was $6 \times 4 \times 2$ m deep. The harbor seal and California sea lion could not haul out during sound exposure sessions. Under test conditions, ambient noise in the pools was similar and very low; it did not mask the hearing test signals

and was similar to that of Sea State 0 (Kastelein et al., 2009a, 2017b, 2023).

Fatiguing Sound

The fatiguing sound used to elicit TTS consisted of a continuous (100% duty cycle for 1 h), constant-amplitude, one-sixth-octave NB sound centered at 8 kHz. A NB sound was used to avoid standing waves, to create a homogenous sound field throughout the pool, and because NB sounds elicit little behavioral response in the study species. One-sixth octave NB sounds were chosen because they are narrow-band (close in bandwidth to a tone). The fatiguing sound was projected at four or five SPLs. Due to reverberations, the sound fields in the pools for the 8 kHz NB sounds were fairly homogenous, and the study animals generally swam throughout the entire pool during sound exposure. Therefore, the mean SPL of all measurement locations in each pool was calculated to indicate the SPL to which the animals were exposed (Kastelein et al., 2022a, 2024a, 2025a).

Hearing Thresholds and Hearing Test Signals

Hearing thresholds were determined using the go/no-go paradigm, a behavioral audiometric technique. Two-thirds of the trials were signal-present trials, and one-third of the trials were signal-absent trials (also called catch trials). The staircase method was used with 2 dB steps. The change from a detected SPL to a non-detected SPL, and vice versa, is called a reversal. The 50% hearing threshold is the mean of all reversal pairs.

The hearing test signal that the study animals were asked to detect before and after the fatiguing sound or ambient noise exposures was a linear upsweep that started and ended at $\pm 2.5\%$ of its center frequency of 11.3 kHz. This frequency, half an octave above the center frequency of the fatiguing sound, was used because it typically showed the greatest TTS in previous studies (Kastelein et al., 2022a, 2024a, 2025a). The hearing test signals had durations of 1,000 ms, including a linear rise and fall in amplitude of 50 ms (Kastelein et al., 2022a, 2024a, 2025a).

Experimental Procedures to Assess Temporary Hearing Threshold Shift

One sound exposure or control test was conducted per day, consisting of (1) a pre-exposure hearing test session in which the baseline hearing threshold of each study animal for 11.3 kHz was quantified; (2) fatiguing sound (the NB sound centered at 8 kHz) exposure for 1 h or ambient noise exposure for 1 h (control); and (3) post-sound exposure (PSE) or post-ambient noise exposure (PAE) hearing test session(s) in which the hearing threshold at 11.3 kHz was quantified for comparison to the

baseline threshold. The PSE and PAE initial TTS levels were determined by measuring the mean unmasked detection threshold in the 1- to 4-min period immediately after the end of the fatiguing sound. This mean threshold was compared with the mean unmasked detection threshold measured before the fatiguing sound or ambient noise exposure.

The PSE hearing test commenced within 1 min after the period of exposure to fatiguing sound or ambient noise. Following initial trials to estimate the SELs that were likely to result in TTS, four or five fatiguing SELs, separated by 6 dB, were tested. This permitted calculation of 6 dB TTS-onset levels (as defined by Southall et al., 2019). We then determined relationships between TTS and SEL in each of the three species, and also compared 6 dB TTS-onset levels to the basic (unmasked) hearing thresholds (Kastelein et al., 2009a, 2017b, 2023).

Results

Hearing Thresholds at 8 kHz

Basic underwater audiograms showed that at 8 kHz, the 50% hearing thresholds of the three study animals were similar: for the harbor porpoise, 61 dB re 1 μ Pa; for the harbor seal, 59 dB re 1 μ Pa; and for the California sea lion, 60 dB re 1 μ Pa (Figure 1; data from Kastelein et al., 2009a, 2017b, 2023).

Temporary Hearing Threshold Shifts

After exposure to the NB sound at 8 kHz, the initial TTS quantified in the 4 min after the sound stopped (TTS₁₋₄) was compared statistically to the shifts (which were close to 0 dB) measured during control sessions. The onset of statistically significant TTS₁₋₄ occurred in the three study animals at different SELs: harbor porpoise: 168 dB re 1 μ Pa²s; harbor seal: 180 dB re 1 μ Pa²s; and California sea lion: 178 dB re 1 μ Pa²s (Table 1).

The 6 dB onset of TTS₁₋₄ (a set value as defined by Southall et al., 2019) in the three study animals

Table 1. The lowest sound exposure level (SEL) at which initial statistically significant temporary hearing threshold shift (TTS₁₋₄) occurred in harbor porpoise F02, harbor seal F02, and California sea lion F01, and the magnitude of the threshold shift (TS). Also shown are the 6 dB TTS-onset SELs, as defined by Southall et al. (2019), for the three study animals.

Species	Statistically significant TTS-onset SEL (dB re 1 μ Pa ² s)	TS (dB)	6 dB TTS-onset SEL (dB re 1 μ Pa ² s)
Harbor porpoise	168	4.9	169
Harbor seal	180	4.4	182
California sea lion	178	7.1	176

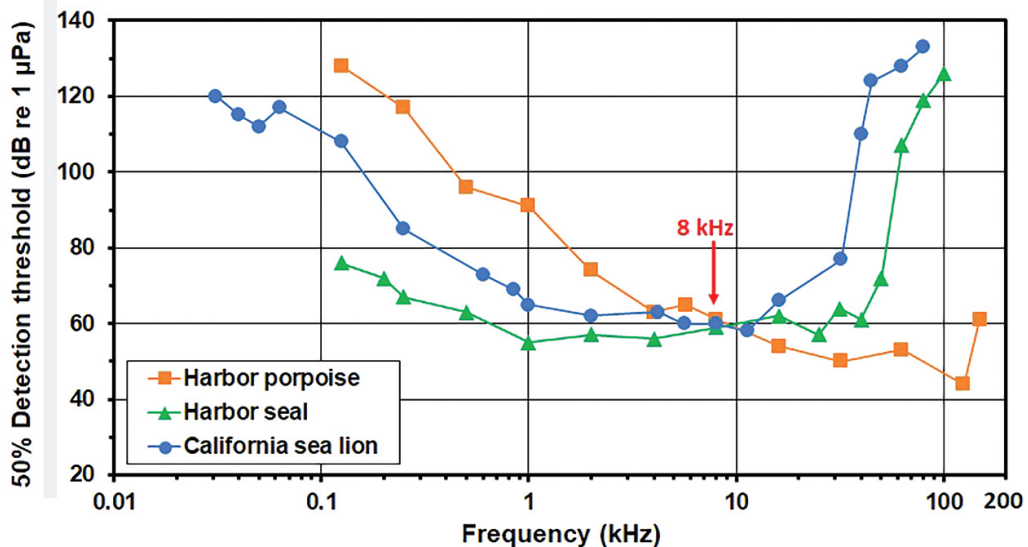


Figure 1. Basic underwater audiograms of three marine mammal species: harbor porpoise F05 (Kastelein et al., 2017b), harbor seal F02 (Kastelein et al., 2009a), and California sea lion F01 (Kastelein et al., 2023). At 8 kHz, the hearing thresholds of the three individuals are similar (also at 11.3 kHz).

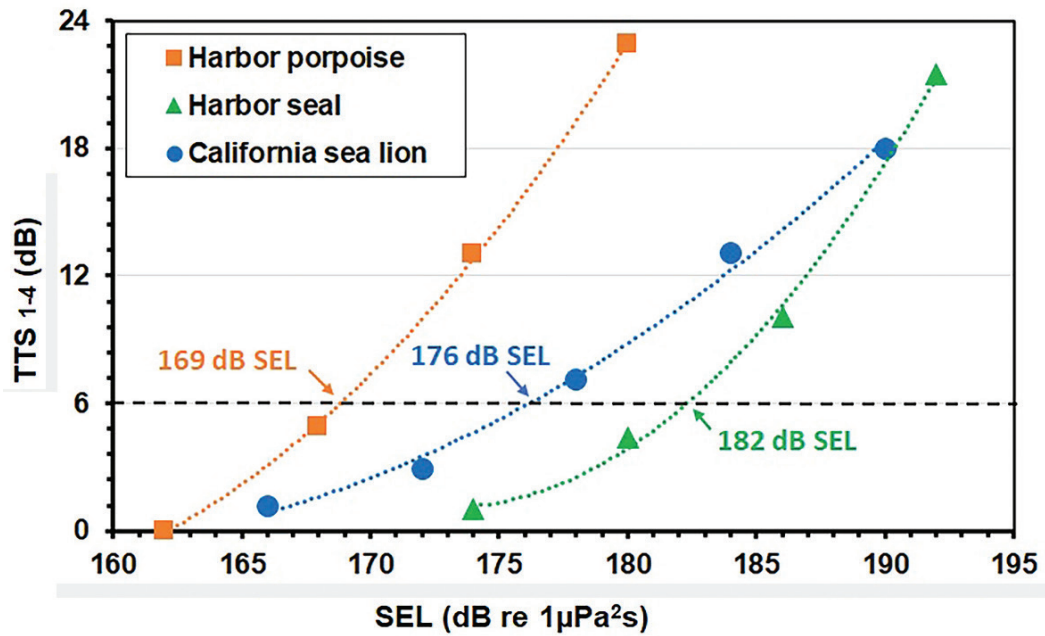


Figure 2. Mean initial temporary hearing threshold shift (TTS_{1-4}) at 11.3 kHz (half an octave above the center frequency of the fatiguing sound) in relation to sound exposure level (SEL) of the fatiguing sound (a continuous, constant-amplitude noise band sound centered at 8 kHz) in three marine mammal species: harbor porpoise F05 (Kastelein et al., 2024a), harbor seal F02 (Kastelein et al., 2025a), and California sea lion F01 (Kastelein et al., 2022a). The SEL at which 6 dB TTS onset occurs (as defined by Southall et al., 2019) differs in the three species (indicated by the three arrows), and the rate of increase of TTS with increasing SEL is less steep in the California sea lion than in the other two species.

Table 2. Mean initial temporary hearing threshold shift (TTS_{1-4} in dB) at 11.3 kHz (half an octave above the center frequency of the fatiguing sound) in relation to sound exposure level (SEL; dB re 1 $\mu\text{Pa}^2\text{s}$) of the fatiguing sound (a continuous, constant-amplitude noise band sound centered at 8 kHz) in three marine mammal species: harbor porpoise F05 (Kastelein et al., 2024a), harbor seal F02 (Kastelein et al., 2025a), and California sea lion F01 (Kastelein et al., 2022a).

SEL (dB re 1 $\mu\text{Pa}^2\text{s}$)	Harbor porpoise TTS_{1-4} (dB)	Harbor seal TTS_{1-4} (dB)	California sea lion TTS_{1-4} (dB)
162	0.0		
166			1.2
168	4.9		
172			2.9
174	13.0	1.0	
178			7.1
180	22.9	4.4	
184			13.1
186		10.1	
190			18.0
192		21.5	

also occurred at different SELs: harbor porpoise: 169 dB re 1 $\mu\text{Pa}^2\text{s}$; harbor seal: 182 dB re 1 $\mu\text{Pa}^2\text{s}$; and California sea lion: 176 dB re 1 $\mu\text{Pa}^2\text{s}$ (Figure 2; Table 1). Once TTS occurred, the rates of increase per dB SEL were higher for the harbor porpoise and harbor seal than for the California sea lion (Figure 2; Table 2).

Discussion

Though TTS data from only one individual per species were available for comparison here, previous studies show that the three study animals are representative of their species in terms of their hearing sensitivity (harbor porpoise: Kastelein et al., 2017b; harbor seal: Kastelein et al., 2009a, 2009b; California sea lion: Kastelein et al., 2023). Comparing the hearing thresholds for 8 and 11.3 kHz to the pre-exposure hearing thresholds in the TTS studies for each study animal also shows that their hearing has remained consistent within a few dB over time (Kastelein et al., 2009a, 2009b, 2017b, 2022a, 2023, 2024a, 2025a). As well as having representative hearing sensitivity, the three study animals are representative of their species in terms of the susceptibility of their hearing to damage by fatiguing sounds, based on comparison with one or a few conspecifics tested with similar methods (harbor porpoise: Kastelein et al., 2024a; harbor seal: Kastelein et al., 2025a; California sea lion: Kastelein et al., 2022a).

Comparing the susceptibility to TTS of the three species shows that the harbor porpoise is most susceptible (TTS occurs at the lowest SEL: 169 dB re 1 $\mu\text{Pa}^2\text{s}$), followed by the California sea lion and then the harbor seal (TTS does not occur until the SEL reaches ~ 182 dB re 1 $\mu\text{Pa}^2\text{s}$). As SEL increases after the onset of TTS, the increase in TTS per dB SEL was ~ 1.5 dB for the harbor porpoise, ~ 1 dB for the California sea lion, and ~ 1.5 dB for the harbor seal. Small differences in the rate of increase of TTS with increasing SEL can result in big differences in the extrapolated PTS-onset SEL. PTS is expected to occur close to when TTS is around 40 dB (Southall et al., 2019).

The differences in susceptibility to hearing damage between the species mean that the extrapolation of data within or between marine mammal hearing groups (Southall et al., 2019) is unlikely to be accurate. Predictions of TTS caused by fatiguing sounds should be based on data from the target species or from close relatives.

Conclusion

Harbor porpoises, harbor seals, and California sea lions have similar basic hearing thresholds at 8 kHz but differ in their TTS-onset SELs (and SPLs in the present study, as exposures to fatiguing sounds centered at 8 kHz all lasted for 1 h).

For 8 kHz sounds, regulations aimed at protecting the hearing of harbor porpoises may effectively protect the hearing of harbor seals and California sea lions as well. The hearing of the harbor porpoise is more susceptible to TTS than that of another odontocete, the bottlenose dolphin (Finneran, 2015), so criteria to protect harbor porpoise hearing from damage by 8 kHz sounds may also be stringent enough to protect the hearing of bottlenose dolphins from damage by sounds at that frequency.

However, hearing damage after exposure to noise differs in the three study species. The pattern of increase in TTS with increasing SEL is steeper in harbor porpoises and harbor seals than in California sea lions. This means that TTS onset occurs at a different sensation level (i.e., at a different number of dB above the basic hearing threshold) in each of the three marine mammal species. Ideally, different policies, recommendations, and regulations for permissible sound exposure are needed to protect each marine mammal species from harm.

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Literature Cited

- Finneran, J. J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. *The Journal of the Acoustical Society of America*, 138(3), 1702-1726. <https://doi.org/10.1121/1.4927418>
- Finneran, J. J., Schlundt, C. E., & Mulsow, J. (2023). Temporary threshold shift in bottlenose dolphins exposed to steady-state, 1/6-octave noise centered at 0.5 to 80 kHz. *The Journal of the Acoustical Society of America*, 154(2), 1324-1338. <https://doi.org/10.1121/10.0020728>

- Kastelein, R. A., Helder-Hoek, L., & Gransier, R. (2019a). Frequency of greatest temporary threshold shift in harbor seals (*Phoca vitulina*) depends on the fatiguing sound level. *The Journal of the Acoustical Society of America*, 145(3), 1353-1362. <https://doi.org/10.1121/1.5092608>
- Kastelein, R. A., Helder-Hoek, L., & Van de Voorde, S. (2017a). Effects of exposure to 53-C sonar playback sounds (3.5-4.1 kHz) on harbor porpoise (*Phocoena phocoena*) hearing. *The Journal of the Acoustical Society of America*, 142(4), 1965-1975. <https://doi.org/10.1121/1.5005613>
- Kastelein, R. A., Helder-Hoek, L., & Van de Voorde, S. (2017b). Hearing thresholds of a male and a female harbor porpoise (*Phocoena phocoena*). *The Journal of the Acoustical Society of America*, 142(2), 1006-1010. <https://doi.org/10.1121/1.4997907>
- Kastelein, R. A., Cornelisse, S. A., Huijser, L. A. E., & Helder-Hoek, L. (2020a). Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise bands at 63 kHz. *Aquatic Mammals*, 46(2), 167-182. <https://doi.org/10.1578/AM.46.2.2020.167>
- Kastelein, R. A., Helder-Hoek, L., Van Acoleyen, L., & Terhune, J. M. (2025a). Temporary hearing threshold shift and testing the equal-energy hypothesis in harbor seals (*Phoca vitulina*) after exposure to a one-sixth-octave noise band centered at 8 kHz. *Aquatic Mammals*, 51(1), 79-95. <https://doi.org/10.1578/AM.51.1.2025.79>
- Kastelein, R. A., Wensveen, P. J., Hoek, L., & Terhune, J. M. (2009a). Underwater detection of narrow noise bands between 0.2 and 80 kHz by harbor seals (*Phoca vitulina*). *The Journal of the Acoustical Society of America*, 126(1), 476-483. <https://doi.org/10.1121/1.3132522>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Defiliet, L. N., & Huijser, L. A. E. (2020b). Temporary threshold shift in a second harbor porpoise (*Phocoena phocoena*) after exposure to a noise band at 1.5 kHz and a 6.5 kHz continuous wave. *Aquatic Mammals*, 46(5), 431-443. <https://doi.org/10.1578/AM.46.5.2020.431>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S., Huijser, L. A. E., & Gransier, R. (2019b). Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise band at 32 kHz. *Aquatic Mammals*, 45(5), 549-562. <https://doi.org/10.1578/AM.45.5.2019.549>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Huijser, L. A. E., & Gransier, R. (2020c). Temporary hearing threshold shift at ecologically relevant frequencies in a harbor porpoise (*Phocoena phocoena*) due to exposure to a noise band centered at 88.4 kHz. *Aquatic Mammals*, 46(5), 444-453. <https://doi.org/10.1578/AM.46.5.2020.444>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S., Huijser, L. A. E., & Terhune, J. M. (2019c). Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 16 kHz. *The Journal of the Acoustical Society of America*, 146(5), 3113-3122. <https://doi.org/10.1121/1.5130385>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S., Huijser, L. A. E., & Terhune, J. M. (2020d). Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 32 kHz. *The Journal of the Acoustical Society of America*, 147(3), 1885-1896. <https://doi.org/10.1121/10.0000889>
- Kastelein, R. A., Helder-Hoek, L., Van Acoleyen, L., Defiliet, L. N., & Terhune, J. M. (2024a). Temporary hearing threshold shift and testing the equal-energy hypothesis in a harbor porpoise (*Phocoena phocoena*) after exposure to a continuous noise band at 8 kHz, and a revised TTS-onset function. *Aquatic Mammals*, 50(5), 445-459. <https://doi.org/10.1578/AM.50.5.2024.445>
- Kastelein, R. A., Helder-Hoek, L., Van Acoleyen, L., Defiliet, L. N., & Terhune, J. M. (2024b). Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to a noise band centered at 32 kHz. *Aquatic Mammals*, 50(2), 107-121. <https://doi.org/10.1578/AM.50.2.2024.107>
- Kastelein, R. A., Helder-Hoek, L., van Kester, R., Huisman, R., & Gransier, R. (2019d). Temporary hearing threshold shift in harbor porpoises (*Phocoena phocoena*) due to one-sixth-octave noise band at 16 kHz. *Aquatic Mammals*, 45(3), 280-292. <https://doi.org/10.1578/AM.45.3.2019.280>
- Kastelein, R. A., Wensveen, P. J., Hoek, L., Verboom, W. C., & Terhune, J. M. (2009b). Underwater detection of tonal signals between 0.125 and 100 kHz by harbor seals (*Phoca vitulina*). *The Journal of the Acoustical Society of America*, 125(2), 1222-1229. <https://doi.org/10.1121/1.3050283>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Defiliet, L. N., Huijser, L. A. E., & Gransier, R. (2021a). Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) due to exposure to a continuous one-sixth-octave noise band centered at 0.5 kHz. *Aquatic Mammals*, 47(2), 135-145. <https://doi.org/10.1578/AM.47.2.2021.135>
- Kastelein, R. A., Helder-Hoek, L., Cornelisse, S. A., Defiliet, L. N., Huijser, L. A. E., & Terhune, J. M. (2020e). Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to one-sixth-octave noise bands centered at 0.5, 1, and 2 kHz. *The Journal of the Acoustical Society of America*, 148(6), 3873-3885. <https://doi.org/10.1121/10.0002781>
- Kastelein, R. A., Helder-Hoek, L., Defiliet, L. N., Huijser, L. A. E., Terhune, J. M., & Gransier, R. (2021b). Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 2 and 4 kHz: Effect of duty cycle and testing the equal-energy hypothesis. *Aquatic Mammals*, 47(4), 394-418. <https://doi.org/10.1578/AM.47.4.2021.394>
- Kastelein, R. A., Helder-Hoek, L., Defiliet, L. N., Kuiphof, F., Huijser, L. A. E., & Terhune, J. M. (2022a). Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 8 and 16 kHz: Effect of duty cycle and testing the equal-energy hypothesis. *Aquatic Mammals*, 48(1), 36-58. <https://doi.org/10.1578/AM.48.1.2022.36>
- Kastelein, R. A., Helder-Hoek, L., Defiliet, L. N., Van Acoleyen, L., Huijser, L. A. E., & Terhune, J. M. (2022b). Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to one-sixth-octave noise bands centered at 0.6 and 1 kHz. *Aquatic Mammals*, 48(3), 248-265. <https://doi.org/10.1578/AM.48.3.2022.248>

- Kastelein, R. A., Helder-Hoek, L., Van Acoleyen, L., Defillet, L. N., Huijser, L. A. E., & Terhune, J. M. (2023). Underwater sound detection thresholds (0.031–80 kHz) of two California sea lions (*Zalophus californianus*) and a revised generic audiogram for the species. *Aquatic Mammals*, 49(5), 422–435. <https://doi.org/10.1578/AM.49.5.2023.422>
- Kastelein, R. A., Helder-Hoek, L., Van Acoleyen, L., Defillet, L. N., Terhune, J. M., & Jennings, N. (2025b). Temporary hearing threshold shift in California sea lions (*Zalophus californianus*) due to a noise band centered at 40 kHz and comparison with shifts due to lower-frequency sounds. *Aquatic Mammals*, 51(1), 13–30. <https://doi.org/10.1578/AM.51.1.2025.13>
- Kastelein, R. A., Parlog, C., Helder-Hoek, L., Cornelisse, S. A., Huijser, L. A. E., & Terhune, J. M. (2020f). Temporary hearing threshold shift in harbor seals (*Phoca vitulina*) due to a one-sixth-octave noise band centered at 40 kHz. *The Journal of the Acoustical Society of America*, 147(3), 1966–1976. <https://doi.org/10.1121/10.0000908>
- Kastelein, R. A., Helder-Hoek, L., Van de Voorde, S., von Benda-Beckmann, A. M., Lam, F-P. A., Jansen, E., de Jong, C. A. F., & Ainslie, M. A. (2017c). Temporary hearing threshold shift in a harbor porpoise (*Phocoena phocoena*) after exposure to multiple airgun sounds. *The Journal of the Acoustical Society of America*, 142(4), 2430–2442. <https://doi.org/10.1121/1.5007720>
- Melnick, W. (1991). Human temporary threshold shifts (TTS) and damage risk. *The Journal of the Acoustical Society of America*, 90(1), 147–154. <https://doi.org/10.1121/1.401308>
- Schaffeld, T., Schnitzler, J. G., Ruser, A., Baltzer, J., Schuster, M., & Siebert, U. (2022). A result of accidental noise pollution: Acoustic flowmeters emit 28 kHz pulses that may affect harbor porpoise hearing. *Frontiers of Marine Science*, 9, 892050. <https://doi.org/10.3389/fmars.2022.892050>
- Schaffeld, T., Ruser, A., Woelfing, B., Baltzer, J., Kristensen, J. H., Larsson, J., Schnitzler, J. G., & Siebert, U. (2019). The use of seal scarers as a protective mitigation measure can induce hearing impairment in harbour porpoises. *The Journal of the Acoustical Society of America*, 146(6), 4288–4297. <https://doi.org/10.1121/1.5135303>
- Southall, B. L., Finneran, J. J., Reichmuth, C., Nachtigall, P. E., Ketten, D. R., Bowles, A. E., Ellison, W. T., Nowacek, D. P., & Tyack, P. L. (2019). Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects. *Aquatic Mammals*, 45(2), 125–232. <https://doi.org/10.1578/AM.45.2.2019.125>
- Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., Jr., Kastak, D., Ketten, D. R., Miller, J. H., Nachtigall, P. E., Richardson, W. J., Thomas, J. A., & Tyack, P. L. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals*, 33(4), 411–521. <https://doi.org/10.1578/AM.33.4.2007.411>
- Yost, W. A. (2007). *Fundamentals of hearing: An introduction*. Academic Press. 326 pp.