Noise emission during the first powerboat race in an Alpine lake and potential impact on fish communities

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In order to assess the effects of high-speed boating on fish communities, noise levels were measured during the first Class 1 powerboat race on the Austrian Lake Traunsee. The noise spectra were compared to natural ambient noise and hearing abilities of four native fish species. Sound pressure levels (SPLs) were significantly elevated during the training heats and the race compared with natural levels, reaching up to 128 dB re 1 μPa (instantaneous SPL) at a distance of 300 m to the powerboats. Continuous equivalent SPLs were significantly lower during training and the pole position race compared to the race itself because fewer boats were simultaneously on the lake. The hearing abilities of the native hearing specialists and generalists were investigated. While carp and roach (two cyprinids) showed enhanced auditory sensitivity typical for hearing specialists, perch and whitefish were much less sensitive to sounds. Comparisons between power boat noise spectra and audiograms showed that the cyprinids can detect the boats up to several hundred meters distance because the main noise energy is well within the most sensitive hearing range. The hearing generalists, however, probably only perceive the first harmonic of the boat noise at close distances.
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I. INTRODUCTION

Noise is an ever-increasing environmental factor in the aquatic environment due to growing anthropogenic activities such as shipping, drilling, seismic explorations or energy production (hydroelectric power plants, offshore windmills) (Myrberg, 1990; Popper, 2003). The effects of noise on aquatic animals may be manifold. Increased noise levels may impair the detection of sounds relevant for acoustic orientation, acoustic communication, prey capture, or predator avoidance by simply masking an animal's hearing. High-intensity sound such as that arising during seismic explorations can even severely damage the sensory epithelia of the inner ear in cod and pink snapper (Enger, 1981; McCauley *et al.*, 2003), injure other inner organs, and induce endocrinological stress responses in several fishes like European sea bass, Atlantic salmon and European freshwater fishes (Sverdrup *et al.*, 1994; Santulli *et al.*, 1999; Smith *et al.*, 2004; Wysocki *et al.*, 2004).

Beyond direct deleterious impacts on the organisms, noise may also have indirect consequences related to ecology, behavior and fitness over the long term. To this date, the focus has been on the impacts of noise on the marine environment, especially on marine mammals (for a review see Richardson *et al.*, 1995). Certain whale species react to approaching vessels by changing their resting and vocalizing behavior and migration routes (Richardson *et al.*, 1995; Lesage *et al.*, 1999). In freshwater habitats, recreational activities, besides traffic or hydroelectric power plants, are largely responsible for increased noise levels. A study on the effects of disturbances on migrating water birds (Schummer and Eddleman, 2003) on a lake in a national wildlife sanctuary has demonstrated that recreational activities account for nearly 87% of all disturbances. Especially boat fishing was found to induce increased alertedness, escape activities and energy expenditure in various bird species.

The effects of boat noise on fishes have mainly been investigated within the framework of population assessment and better management of catch rates in fishery. Such studies were nearly exclusively conducted in the marine environment.

Behavioral responses (e.g., avoidance reactions) of herrings and cods have been observed in the presence of different types of vessel noise in the lab (Boussard, 1981; Schwarz and Greer, 1984), but also in the field (Vabø *et al.*, 2002; Mitson and Knudsen, 2003; Handegard *et al.*, 2003). In the latter, fishes actively avoided different kinds of vessels by diving reactions and horizontal displacement. Groups of spawning rudds and roaches in the Meuse River (Belgium) were observed to actively avoid high-speed boating (Boussard, 1981). Wysocki *et al.* (2004) are showing that boat noise results in an increase in cortisol secretion in European freshwater fishes.

The first Class 1 Powerboat Race in a freshwater lake took place at the Austrian Lake Traunsee in early September 2003. Powerboat racing (top speed 270 km/h) usually takes place offshore in the marine environment (e.g., in Dubai, Quatar, Portugal, Germany, to name just a few). In Travemünde (Germany), environmental impact assessment on the powerboat races are furnished annually in order to elaborate the factors potentially affecting the adjoining marine and terrestrial protected areas, and to minimize conflicts with the local population and authorities (Morgenroth 2002, 2003). With regard to the aquatic environment, most concern has

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been expressed about hydrological forces and turbidity in view of the blue mussels and about potential collisions between powerboats and whales. However, the lack of underwater noise measurements is regarded as a main shortcoming for the prognosis of noise effects, and the necessity for such measurements in future surveys has been stressed.

In order to provide a basis for assessing the potential effects of powerboat races on animal communities in and around an alpine lake, the local district authorities in Upper Austria required noise measurements in air and under water, echo-sounder studies on fish distribution before and after the race, and the monitoring of birds during the Class 1 Powerboat Race on Lake Traunsee in early September 2003. The decisive factor for the order to conduct underwater noise measurements and echo-sounder studies was the concern of local fishermen that whitefish stocks might be disturbed. The European whitefish (*Coregonus lavaretus* L.) is not only the dominant but also the most important commercially used species of this and neighboring lakes (Wanzenböck *et al.*, 2002a). During the past years, the population in Lake Traunsee has collapsed due to declining productivity paralleling a pronounced oligotrophication of the ecosystem and continuing high fishing pressure (Wanzenböck *et al.*, 2002b).

Our study is the first to describe underwater noise emissions and noise levels of powerboats in a lake and to determine the hearing abilities of several native fish species (with different hearing abilities). This should enable us to calculate the distance over which powerboats can be detected by fish and to estimate the potential impacts on fish communities. Our paper should enhance public awareness on the effects of recreational boating on fish communities.

II. MATERIAL AND METHODS

A. Study site

Lake Traunsee is situated in the Traun River drainage basin in the lake district ''Salzkammergut'' east of Salzburg, Austria, 422 m above sea level (Fig. 1). It is a typical oligotrophic, deep (mean depth: 90 m, maximum depth: 191 m) alpine lake with rather low retention times due to flushing by the large Traun River (Wanzenböck *et al.*, 2002b). The fish community is dominated by European whitefish (*Coregonus lavaretus* L.) as well as by salmonids such as the arctic charr (*Salvelinus alpinus*), by perches such as *Perca fluviatilis*, and eight cyprinid species, e.g., the roach *Rutilus rutilus* and the carp *Cyprinus carpio* (Wanzenböck *et al.*, 2002a).

Data collection was performed from a 10 m motor sailboat in the afternoon of 13 September and in the morning of 14 September 2003. The boat was anchored at the embankment of the quarry of Karbach (Fig. 1, Position 2), which is on the east bank of the lake. This site was surrounded by mountains and an underwater rock face plunges down to about 140 m water depth. The hydrophone was suspended at a depth of about 1.5 m. The powerboats passed by here at high speed (~270 km/h) because this position was at the longest straights of the course (Fig. 1). The shortest distance to the powerboats was ~300 m (an official security zone prohibited closer access to the powerboats).

The weather was rainy on 13 September (air temperature about 16 °C, water temperature about 15 °C) and became rather dry and partly sunny towards the end of the measurements on 14 September (air temperature 16 °C in the morning, 20 °C around noon; water temperature 16 °C).

In addition, on 12 September (afternoon) and 13 September (morning), measurements were performed at a site near the confluence of the Traun River (hydrophone depth 1–1.5 m) in the southern part of the lake off Ebensee (Fig. 1, Position 1). Because the river was spating due to heavy rains on previous days, strong currents caused the boat to drift and produced high ambient noise levels. Therefore, data from this recording site were excluded from further analysis.

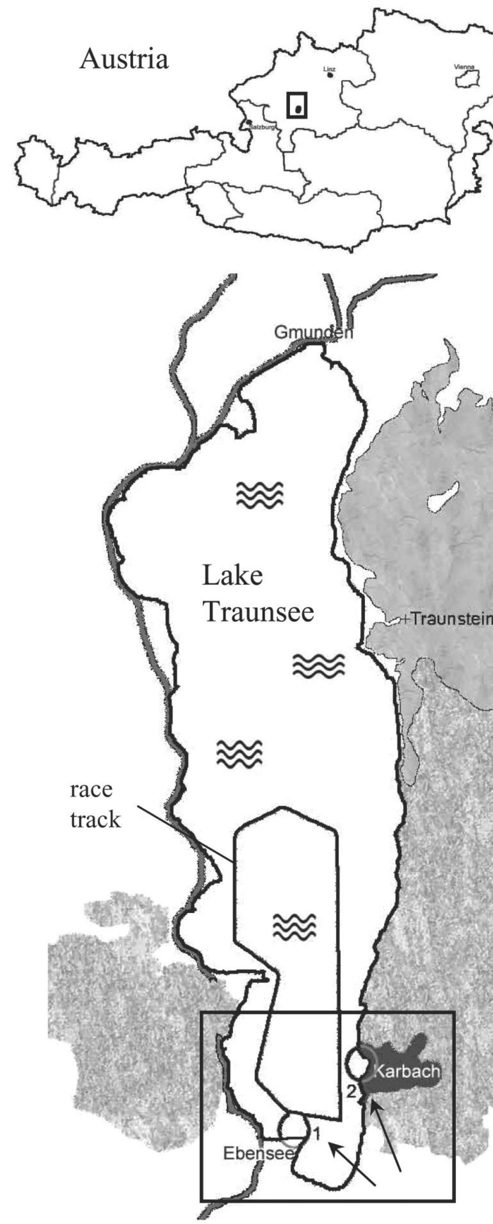

FIG. 1. Map of Lake Traunsee and the race track of the Class 1 powerboat race. (1) and (2) indicate the two measuring positions (Position 1, Position 2; marked by arrows); for more details see text. Gray textures: mountain area.

B. Noise measurements and recordings

Sound pressure levels of ambient and boat noise were measured using a sound level meter (Brüel and Kjaer 2238 Mediator), a Brüel and Kjaer 2804 power supply and a Brüel and Kjaer 8101 hydrophone. Two SPL measures were obtained: (1) The instantaneous SPL (L_{LSP}, L-weighted, 5 Hz to 20 kHz, RMS fast), to assess the variability of both the ambient and the powerboat noise, and (2) the equivalent continuous SPL (L_{Leq}), averaged over 60 s. The L_{Leq} is a measure of the averaged energy in a varying sound level and is commonly used to assess environmental noise (ISO 1996). SPL measurements were made for one to two minutes. During each period the $\mathrm{L_{LSP}}$ was noted every 5 s, and at the end we noted the L_{Leq} as well (the B & K Mediator allows parallel reading of four different noise measures).

Underwater noise was recorded on a DAT recorder (Sony TCD 100) connected to the power supply and hydrophone. Recordings were made during the heats (training, pole position race, and the race itself) and just before and after the heats, when neither powerboats nor other motor boats were cruising on the lake, to get recordings under ''quiet'' conditions. The minimum recording period was 1 min, but for some recordings—especially during the race itself—this period was elongated up to 5 min and more. Immediately before and/or after the sound recordings, L_{LSP}- and L_{Leq} were measured. Thus, it was possible to attribute SPL values to each of the recordings.

C. Sound analysis

All sound recordings were analyzed using STX 2.17 (sampling frequency 44.1 kHz), the sound processing software developed by the Research Laboratory of Acoustics at the Austrian Academy of Sciences. Two ambient noise recordings were made during a period of 10 h (4 h during the pole position race, 5 h during training, 1 h during the race). A total of 107 s of ambient noise and 3579 s of boat noise (1235 s training, 1018 s pole position race, and 1326 s race) were analyzed.

1. Noise spectra calculations

The relative noise spectra of mean ambient noise and powerboat noise were calculated. Ambient noise (AN) refers to ''quiet'' conditions when neither powerboats nor other motor boats were cruising on the lake. Powerboat noise (PN) is the noise recorded when the powerboats were closest to the recording site (minimum distance of 300 m).

For the absolute AN spectra calculation, FFTs for each recording under quiet conditions were averaged and absolute spectra calculated using the L_{Leq} measured immediately before and after the recordings. For the PN spectra calculations, 59 noise segments of 5 s duration were selected from 9 recordings at those parts with highest sound amplitude (corresponding to minimum distance of the boats) and equated to the corresponding L_{LSP} for spectrum level and distance calculations (Fig. 3).

Averaged sound spectra of the recordings were calculated by a fast Fourier transform (FFT) analysis using a filter bandwidth of 1 Hz. These spectra were then exported as ASCII Files and imported into EXCEL, and the relative spectral values were transformed to linear values using Eq. (1):

$$A_i = 10\hat{}(a_i/10), \tag{1}$$

where A_i are the linear spectral amplitude values, a_i the logarithmic spectral amplitude values. From these values, the relative root-mean square (rms) was calculated by Eq. (2):

$$e = 10 * \log \sum Ai, \tag{2}$$

where e is the relative rms value calculated from the spectral amplitudes. The relative rms was then equaled to the absolute L_{LSP} measured with the sound level meter immediately before and/or after the recording, and the relative spectral levels were recalculated into absolute spectral levels.

2. Statistical analysis

The L_{Leq} levels measured at four conditions (ambient noise, training, pole position race, and race) were compared by a one-way ANOVA, followed by Scheffé post hoc tests. Instantaneous SPL measures (L_{LSP}) were not normally distributed, nor were variances homogeneous. Therefore, nonparametric statistic tests were used. Values obtained at the four different measurement conditions were compared by a Kruskal–Wallis test. The Mann-Whitney-U test was used for further pair wise comparisons. All statistical tests were run using SPSS 11.5.

D. Auditory sensitivity measurements

1. Animals

Test subjects were six Common carps *Cyprinus carpio* [99.2–155 mm standard length (SL), 29–61.4 g body mass (BM)] from a pond near Vienna, seven European perches *Perca fluviatilis* (85.7–97.8 mm SL; 10.6–16.9 g BM) and six European whitefish *Coregonus lavaretus* (93.7–111.8 mm SL; 8.2–16 g BM). The latter two species were obtained from local hatcheries near Traunsee. In addition, two specimens of roach *Rutilus rutilus* (135 and 136 mm SL; 45.7 and 43.7 g BM) obtained from a fisheries pond in Lower Austria were measured.

All animals were kept in planted aquaria whose bottoms were covered with sand, equipped with half flower pots as hiding places, filtered by external filters, and maintained at a 12L:12D cycle. The temperature in the holding tanks was around 21 °C, for the whitefish 16 °C. The fish were fed live *Tubifex* sp., chironomid larvae or commercially prepared flake food (Tetramin, Tetrapond®) daily. No submerged filters or air stones were used in order to reduce noise in the holding tanks. All experiments were performed with the permission of the Austrian Commission on Experiments in Animals (GZ 68.210/50-Pr/4/2002).

2. Auditory evoked potential (AEP) recordings

The AEP recording protocol used in this study followed that recently described in Wysocki and Ladich (2002, 2003) and Amoser and Ladich (2003). Therefore, only a brief summary of the basic technique is given here. During the experiments, the fish were mildly immobilized with Flaxedil (gallamine triethiodide, Sigma). The dosage used was 0.5–1.3 $\mu \mathrm{g\,g^{-1}}$ for *C. carpio*, 1.3–3.3 $\mu \mathrm{g\,g^{-1}}$ for *P. fluviatilis*, 2.4–

5.8 $\mu g\,g^{-1}$ for *C. lavaretus*, and 0.8 and 1.5 $\mu g\,g^{-1}$ for *R. rutilus*. This dosage allowed the fish to retain slight opercular movements during the experiments but without significant myogenic noise to interfere with the recording. Test subjects were secured in a bowl-shaped plastic tub (37 cm diameter, 8 cm water depth, 2 cm layer of fine sand) lined on the inside with acoustically absorbent material (air-filled packing wrap) in order to reduce resonances and reflections (see Fig. 1 in Wysocki and Ladich, 2002). Fish were positioned below the water surface (except for the contacting points of the electrodes, which were maximally 1 mm above the surface) in the center of the plastic tub.

A respiration pipette was inserted into the subject's mouth. Respiration was achieved through a simple gravity-fed water circulation system. Temperature during the experiments was 17.6±0.6 °C (SE) for *C. lavaretus* and 21.5 ±0.4 °C (SE) for the other 3 species. The AEPs were recorded using silver wire electrodes (0.25 mm diameter) pressed firmly against the skin. The portion of the head above the water surface was covered by a small piece of Kimwipes tissue paper to keep it moist and to ensure proper contact during experiments. The recording electrode was placed in the midline of the skull over the region of the medulla and the reference electrode cranially between the nares. Shielded electrode leads were attached to the differential input of an a. c. preamplifier (Grass P-55, gain 100×, high-pass at 30 Hz, low-pass at 1 kHz). The plastic tub was positioned on an air table (TMC Micro-g 63-540) which rested on a vibration-isolated concrete plate. The entire setup was enclosed in a walk-in sound-proof room, which was constructed as a Faraday cage (interior dimensions: 3.2 m×3.2 m×2.4 m).

Both sound stimuli presentation and AEP waveform recording were accomplished using a Tucker-Davis Technologies (Gainesville, FL, USA) modular rack-mount system (TDT System 3) controlled by a Pentium 4 PC containing a TDT digital processing board and running TDT BioSig RP Software.

3. Sound stimuli

Sound stimuli waveforms were created using TDT SigGen RP software and fed through a power amplifier (Alesis RA 300). A dual-cone speaker (Tannoy System 600, frequency response 50 Hz–15 kHz±3 dB), mounted 1 m above test subjects in the air, was used to present the stimuli during testing.

Sound stimuli consisted of tone bursts which were presented at a repetition rate of 21 per second. Hearing thresholds were determined at frequencies of 100, 300, 500, 800, 1000, 2000, 3000, and 4000 Hz for *C. carpio* and *R. rutilus*, and of 100, 200, 300, 500, 800, and 1000 Hz for *P. fluviatilis* and *C. lavaretus*, presented in random order. The duration of sound stimuli increased from two cycles at 100–300 Hz up to eight cycles at 4000 Hz. Rise and fall times were one cycle at 100 and 200 Hz and two cycles at all other frequencies. All bursts were gated using a Blackman window. For each test condition, stimuli were presented at opposite polarities (180° phase shifted), and the corresponding AEPs averaged by the Bio-Sig RP software in order to eliminate stimulus artifacts. Sound pressure levels of tone-burst stimuli were reduced in 4 dB steps until the AEP waveform was no longer apparent. The lowest SPL level for which a repeatable AEP trace could be obtained, as determined by overlaying replicate traces, was considered the threshold (Kenyon *et al.*, 1998).

A hydrophone (Brüel and Kjaer 8101, frequency range: 1 Hz–80 kHz±2 dB; voltage sensitivity: −184 re 1 V/μPa) was placed close to the right side of the animals (2 cm apart) in order to determine absolute SPLs underwater in close vicinity of the subjects. Control measurements showed that, in accordance with theoretical expectations (due to increasing distance from the loudspeaker), SPLs decreased with increasing distance from the center of the tub as well as with increasing depth. Our sound-pressure-sensitive hydrophone responded exactly to any attenuation in SPL generated by the BioSig software and played back via the air loudspeaker.

Only measurements of sound pressure were performed; in any acoustic field this is the adequate measure of the degree of auditory stimulation in pressure-sensitive fish such as otophysines (Fay and Popper, 1974). Although hearing generalists such as the perch and whitefish perceive only the kinetic component of sound, hearing thresholds were given as SPL levels in order to enable their auditory sensitivity to be compared with ambient noise spectra (which are always given in pressure units) and to calculate possible effects.

III. RESULTS

A. Radiated noise levels

The L_{Leq} measured at the different times (ambient, pole position race, training, race) differed significantly (one-way ANOVA: $F_{3,35}=76.03$; $p<0.001$). A Scheffé post-hoc test revealed that the noise level during the race differed from all other noise levels ($p<0.001$). Similarly, the ambient noise (AN) was different from all the other conditions ($p<0.001$), whereas the noise levels at the pole position race and during the training were not significantly different from each other ($p=0.156$). On the average, the L_{Leq} was elevated by 14.76±1.01 dB during the race relative to quiet conditions (AN) and was 3.56±0.63 to 5.34±0.74 dB louder than during the pole position race and the training sessions (Fig. 2).

The instantaneous noise levels (L_{LSP}) were not normally distributed, nor were variances homogeneous (Table I). Therefore, nonparametric statistical tests were used. L_{LSP}s were compared between 4 measurement conditions: AN, pole position race, training, race. A Kruskal–Wallis-test revealed significant differences between the different measurements: $\chi^2_{3,216}=153.34$; $p<0.001$. Mann–Whitney-U tests revealed that only L_{LSP} between the pole position race and the race did not differ significantly ($U_{31,36}=547$; $p=0.884$). All other pairings were significantly different.

B. Noise spectra

Figures 3 and 4 illustrate that the main sound energies were concentrated below 5 kHz. PN emissions were harmonic with a mean fundamental frequency of 417±2.7 Hz (range: 400–445 Hz, $n=67$). Four to 11 harmonics were

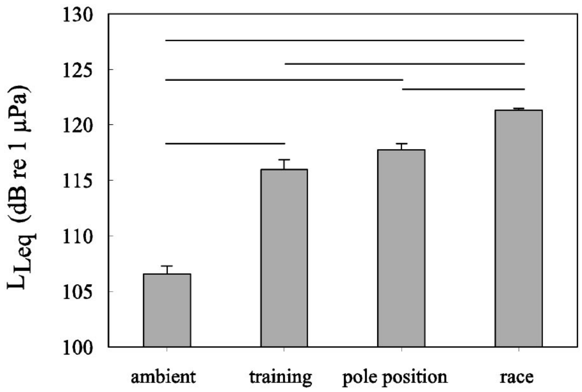

FIG. 2. Mean (±SE) equivalent continuous SPLs (L_{Leq}) of the ambient noise and the noise levels measured during training, the pole position race and the race itself. All possible pairwise tests were statistically different at the level of $p<0.001$ except for training vs pole position race.

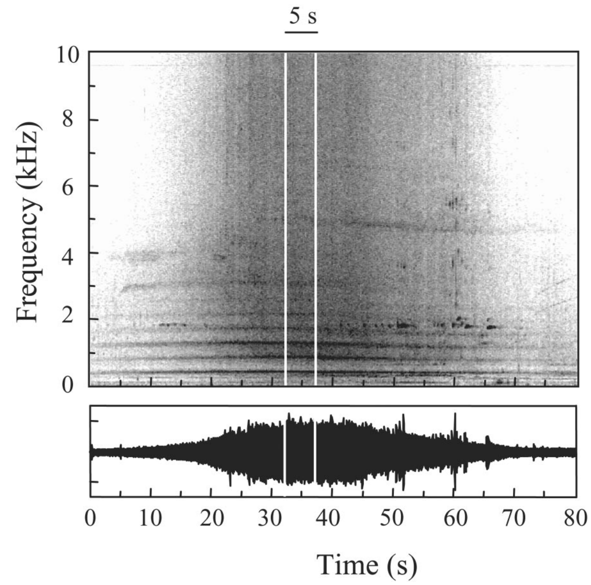

FIG. 3. Sonagram (above) and oscillogram (below) of the powerboat noise recorded during the race. The white bars indicate the 5 s time period chosen for calculating the PN noise spectra. Filter bandwidth 10 Hz, sampling frequency 44.1 kHz, 50% overlap, window: Blackmann Harris.

detectable in the amplitude spectrum [Figs. 3 and 4(b)]. The drop off at higher frequencies differed between noise conditions. AN levels were relatively high at low frequencies, with a peak of 93 dB at 110 Hz, and decreased by about 1.8 dB per kHz between 0.5 and 12 kHz; they then showed a slight increase again before falling off more steeply (2.9 dB per 1 kHz) to 20 kHz (Fig. 4). The powerboat noise decreased by 0.8 dB per kHz above 3 kHz which is much less than in the AN, indicating that powerboat noise levels remain much higher in the upper frequency range than AN.

C. Hearing sensitivity of the fish species

Both otophysines, *C. carpio* and *R. rutilus*, were sensitive to high-frequency sounds (up to at least 4000 Hz, the highest frequency tested) and had sensitivity maxima between 500 and 1000 Hz (Fig. 5). AEPs of *C. lavaretus* could only be obtained up to 800 Hz, those of *P. fluviatilis* up to 1000 Hz. Sensitivity maxima were found at 300 Hz. The latter two species were up to 50 dB less sensitive to tone bursts than the otophysines (Fig. 5).

IV. DISCUSSION

A. Powerboat noise emissions

Very little data is available on SPL measurements and noise spectra of recreational boats or vessels other than commercial or military ships (Arveson and Vendittis, 2000; Malinowski and Gloza, 2002), and most of these data were assessed in the marine environment. In an attempt to compare the noise characteristics of six research vessels, Mitson (1993) stressed that SPLs and frequency spectrum are extremely variable in relation to speed, load, pitch angle of

TABLE I. Range of instantaneous noise levels (L_{LSP}) measured during the 4 noise conditions. All L_{LSP}-values are given in dB re 1 μPa.

Condition	Min. L_{LSP}	Max. L_{LSP}
Ambient noise	103	114
Training	122	126
Pole Position Race	124	127
Race	124	128

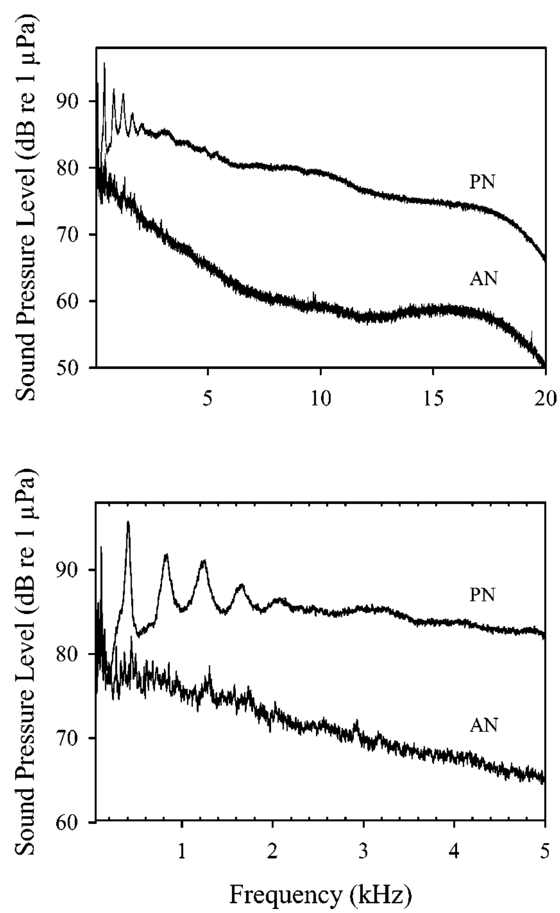

FIG. 4. Noise spectra recorded during the different conditions in Lake Traunsee during the powerboat race in 2003. Shown are the mean spectra computed from 107 s AN and 350 s PN. The lower graph gives a detail of the noise spectra within the hearing range of fishes (50–5000 Hz).

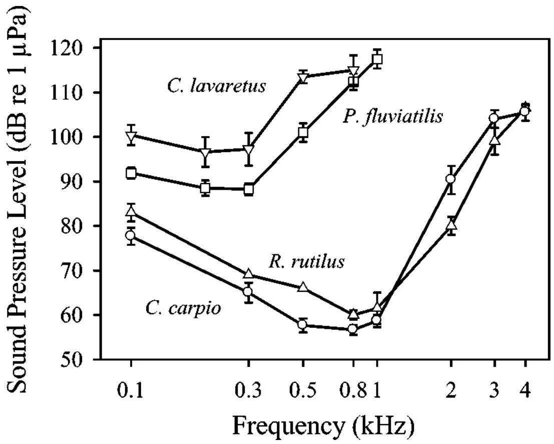

FIG. 5. Audiograms (mean±SE) of the four selected fish species, determined using the AEP-recording technique.

propeller and age of the vessel, which makes it difficult to compare different studies. Noise from merchant ships with keel aspect source levels ranging between 178 and 192 dB re 1 μPa (at 1 m) can elevate the natural ambient noise in the marine environment by 20–30 dB in many areas (Arveson and Vendittis, 2000); smaller ships ($<$60 m of length) produce keel aspect wideband source levels of 140–167 dB and were found to elevate natural ambient noise by 10–40 dB. The latter observation agrees with our study where, during the race, the equivalent continuous SPL exceeded the natural ambient noise by about 15 dB on the average, whereby the minimum distance to the boats was 300 m and the source level was calculated to be 180 dB at 1.2 m. Boussard (1981) described 1/3 octave band levels of up to 140 and 160 dB near cruising barges and high speed boats, respectively, in the Meuse River.

A characteristic feature for the radiated noise of surface ships is peaks in the frequency range below 100 Hz (Malinowski and Gloza, 2002), sometimes also at higher frequencies, depending on propeller, engine and load. For example, the position of peaks within the frequency spectrum of the FRV "Thalassa" changed when trawling conditions were simulated by towing a loaded barge on the surface. Mitson (1993) attributes the increase in high-frequency noise level during the trawling simulation to the different propeller pitch angles. Another research vessel described in that report, the FRV "Explorer," which is a steam-powered vessel, showed a peak at 830 Hz when in free-ranging mode, this "singing" being caused by the propeller. This tone is lost during trawling because of the increased cavitation level.

The radiated noise of the powerboats also showed a peak at about 417 Hz, which fits well to the above-mentioned vessels. However, the powerboat noise shows harmonic characteristics as well, a feature not described for the research vessel and clearly audible when listening to the recordings. One feature that powerboat noise has in common with other boat noise is the relatively high levels in the low frequency range and the slow fall off at higher frequencies (in the case of the powerboats above 3 kHz).

Noise levels (L_{Leq}) were significantly higher during the race compared to the training heat and the pole position race. This surely was caused by the larger number of boats racing simultaneously on the lake during the race (maximal 1 and 2 boats during training heat and pole position race as compared to 5–9 boats during the race itself). Noise levels during all heats (training, pole position race, and race) were significantly above the natural ambient noise, even measured at a distance of 300 m. Note that the natural ambient noise measured in Lake Traunsee is quite high for a lake (about 106 dB), which may be attributed to the fact that the Traun River flows rather rapidly through the Lake from its south end in Ebensee to the north end, causing a strong current throughout the lake. The mean noise level in the neighboring Lake Mondsee is ~98,5 dB (pers. obs.).

B. Hearing abilities of lake fishes

The investigated species are typical representatives of hearing specialists and generalists in the lake investigated. In general, fishes without accessory hearing structures ("hearing generalists") are sensitive to particle motion and are only able to detect low-frequency sounds. Typical hearing generalists in European freshwaters are perch (*Perca fluviatilis*), pike (*Esox lucius*), salmonids (trouts and charrs), and whitefish (coregonids). The ability to transmit oscillations of air-filled cavities within the body enables several groups ("hearing specialists;" Hawkins and Myrberg, 1983) to perceive not only the kinetic but also the pressure component of sound; this improves their hearing sensitivity by allowing an extension of the hearing range and by lowering the hearing thresholds (Popper and Fay, 1993). The predominant group of hearing specialists in European freshwaters are cyprinids, which belong to the otophysines. This group is characterized by a chain of bony ossicles, known as the Weberian apparatus, connecting the swim bladder to the inner ear (for a recent review, see Ladich and Popper, 2004).

Knowledge of the hearing abilities of native European freshwater fish species is sparse. A sound pressure audiogram up to 300 Hz with a maximum sensitivity of 86.5 dB re 1 μPa at 100 Hz has been established for European perch and pike-perch (up to 800 Hz) (Wolff, 1967, 1968). No data are available on coregonids. Within the salmoniforms, only the Atlantic salmon, *Salmo salar*, was investigated; this species shows particularly low hearing sensitivity with the most sensitive hearing at about 160 Hz (hearing thresholds 95 dB re 1 μPa; Hawkins und Johnstone, 1978). By contrast, cyprinids such as carp and roach possess excellent hearing abilities up to several kHz, with best sensitivities of about 60 dB re 1 μPa between 0.5 and 1.0 kHz. Data on the carp and roach agree well with previous audiograms in cyprinids in respect of hearing range and sensitivity (koi carp: Popper, 1972; goldfish: Ladich 1999, Ladich and Wysocki, 2003). Most cyprinids apparently possess quite similar hearing capabilities, enabling conclusions to be drawn about other cyprinids which have not yet been investigated. The audiograms of perch and whitefish should be interpreted with caution because hearing generalists are only sensitive to particle motion and not to sound pressure. However, it was neither possible to measure boat noise levels in terms of particle motion nor to calculate particle motion sound spectra. The present sound pressure audiograms of the hearing generalists are de-

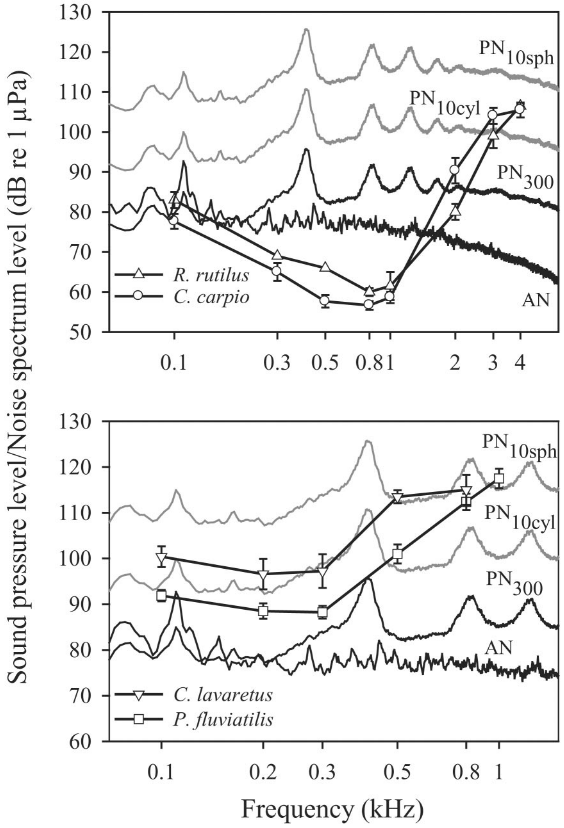

FIG. 6. Audiograms of the cyprinids (above) and the hearing generalists (below) compared with different noise spectra. AN=ambient noise (without boats), PN_{300}=powerboat noise at a distance of 300 m (measured), PN_{10cyl}, PN_{10sph}=noise 10 m away from the boats, considering cylindrical (attenuation of 3 dB/dd) and spherical spreading (attenuation of 6 dB/dd), respectively (calculated). Omitted are potential filter properties of the medium during sound propagation and distortions of the frequency content. Note the difference in *x*-axes ranges in Fig. 4 (linear) and this figure (logarithmic).

termined for comparative purposes and should not be regarded as absolute hearing thresholds.

C. Possible detection distance of boat noise

A comparison of hearing sensitivities measured with absolute powerboat (+ambient) noise spectra shows that the main energies of the boat noise lie within the most sensitive hearing range of the cyprinids [Fig. 6(a)]. Depending on the distance of the boats, their noise emitted is more than 45 dB (distance 10 m) above the hearing thresholds of the fish (at 800 Hz). Even at distances of 300 m, the spectral noise levels are ~30 dB above the hearing threshold measured under relative quiet laboratory conditions. By contrast, hearing generalists such as perch and whitefish most likely only detect the first harmonic (containing the peak energy of the boat noise) at closer distances to the boats [below 10 m, Fig. 6(b)].

When estimating the detection distance of a sound source, however, the prevailing ambient noise must be taken into account. Figure 6(a) illustrates that the ambient noise spectrum levels in Lake Traunsee are higher than the hearing thresholds of cyprinids. Thus, the hearing of these species in the natural habitat is masked, which means that signal detection is impaired. It is therefore insufficient to compare audiograms established under quiet laboratory conditions with field sound spectra in order to calculate the detectable distance of boat noise. Another key factor to consider is the signal-to-noise ratio at threshold level (S/N at threshold) of the fish. It is a measure of how much the signal energy must lie above the background noise for the signal to be detected by the animal and is defined as the difference (in dB) between the masked hearing threshold and the spectrum level of the masking noise (Chapman and Hawkins 1973). In general the S/N ratios at threshold are independent of the actual noise level over wide noise ranges, a phenomenon common to fishes as well as mammals (Fay 1974, 1988, Yost 2000).

Taking those two parameters into account, we calculate—according to Southall *et al.* (2000)—the approximate maximum distance at which the different investigated species can potentially detect the noise emitted by the powerboats. This is only a crude estimate because several other details on the actual sound propagation characteristics at different sites in the lake, i.e., bottom morphology, absorption, shadow zones due to refraction, salinity, temperature clines, etc., will also influence the detection limit. We apply rather strict criteria in our calculation, so this distance is likely to be underestimated. We concentrated on the first harmonic (around 400 Hz) of the boat noise, where the energy maximum is concentrated. S/N ratios at threshold at several frequencies are available for the goldfish, which has an audiogram very similar to carp and roach. Therefore, S/Ns at threshold for other cyprinids are likely to be similar to those of goldfish. In the following calculation, we assumed a $10 \log R$ spreading for shallow waters (according to Southall *et al.*, 2000). Based on a S/N at threshold of 15 dB at 400 Hz, the main energy of noise, (by comparing and interpolating data from the literature; Fay, 1974; Wysocki and Ladich, in press), and on an ambient noise spectrum level of 77 dB re 1 μPa, the hearing threshold would be 92 dB re 1 μPa in this lake. Assuming that the powerboat source spectrum level is 120 dB at 1.2 m under the assumption of cylindrical sound spreading (3 dB/dd), the powerboats should be detectable by otophysine fish at distances of almost 400 m even in the shallow banks of the Lake Traunsee. When we add the S/N at threshold level to the AN spectrum level, the result (92 dB) is 4 dB lower than the powerboat spectrum level at a distance of 300 m (96 dB); this supports the above calculation of the audible powerboat distance [Fig. 6(a)].

For the hearing generalists [Fig. 6(b)], we estimated a S/N ratio at threshold of 20 dB based on interpolations available for other hearing generalists like cod and sunfish (Hawkins and Chapman, 1975; Wysocki and Ladich, in press) at 400 Hz. At this frequency, the European perch's hearing threshold could just be masked (AN spectrum level plus S/N at threshold=97 dB vs interpolated hearing threshold of 95 dB). We therefore included the 97 dB originating from masked hearing into the calculation. Under these assumptions, perch probably perceive the boats up to a distance of 200 m. Whitefish are not likely to be masked in the lake (interpolated hearing threshold of 105 dB at 400 Hz), leading us to operate with absolute hearing threshold values. The maximum distance at which they can detect the boats is roughly 30 m. Note again the restrictions related to interpreting the sound pressure hearing thresholds of perch and whitefish and thus the estimated distance over which they can detect the boat noise. Nonetheless, the general statement that powerboat noise affects hearing-specialized cyprinids over much wider distances than percids or coregonids remains valid. At the audible distances, the boat noise will interact with other sound sources and additionally mask acoustic signals relevant for the fish, such as sounds from prey or predators.

Beyond affecting hearing (Scholik and Yan, 2002), boat noise may also induce disturbances. There are several indications that fishes are disturbed by shipping. Certain investigations, mainly performed in the marine environment, show that fishes react to different extents to ship noise. Cods (*Gadus morhua*) significantly altered their behavior during and after the passage of a bottom-trawling vessel. They initially reacted by diving, then with horizontal movements away from the ship (Handegard *et al.*, 2003). No data on noise levels emitted by the vessel were given. Herring reacted differently to loud and quiet boats (Vabø *et al.*, 2002). Their reactions were already significant at distances of 220–270 m to a 3 t vessel cruising at 10.9 knots. These observations are interesting when regarding the fact that herrings are less sensitive than perches and coregonids measured in our study (best sensitivity according to Mann *et al.* (2001) 100 dB re 1 μPa). Based on these data and vessel speeds, Mitson and Knudsen (2003) calculated that this vessel type radiates 144–164 dB at 8 knots, which has the potential to induce fish reactions between 79 and 790 m. Fernandes *et al.* (2000) reported no reaction in herring near a noise-reduced vessel complying with ICES CRR 209 recommendations. The ICES CRR No. 209 (Mitson 1995) stressed the importance of noise reduction at vessel motors, especially for research vessels surveying fish resources. Based on available data on fish hearing capacities and behavioral reactions to noise, guidelines for noise specifications of vessels that would not affect the fishes were established. In that report, spectral levels (in 1 Hz bands) of 130–134 dB re 1 μPa at 1 m for frequencies up to 2 kHz (the main hearing bandwidth of most fishes) were recommended in order not to alter fish behavior.

Although our knowledge about noise control is increasing in the marine environment, data on freshwaters remain sparse. Underwater video recordings of rudds and roaches in the Meuse River (Belgium) showed that the fishes actively avoided high-speed boats (Boussard, 1981). The flight reactions started at distances of approximately 5 m. Based on playback experiments in the lab, the author concluded that this reaction is exclusively induced by the acoustic stimuli when an amplitude of 125 dB is reached. Comparing this to data on herring and cod reactions, it seems likely that several fish species can hear a noise source over wide distances. Stress and avoidance reactions during the race must be assumed because noise levels causing stress reactions and elevation in cortisol levels in otophysines (white noise: Smith *et al.*, 2004; ship noise: Wysocki *et al.* 2004) were reached in vicinity of the powerboats. Our assumption is supported by reports of local fishermen who observed an increase in catch rates 1 to 2 days after the powerboat race (J. Wanzenböck, pers. comm.). Higher catch rates are probably due to a higher swimming activity of fishes following startling by the powerboat noise in Lake Traunsee.

V. CONCLUSIONS

Powerboats generated noise levels of ~180 dB re 1 μPa at 1 m distance during the first Class 1 powerboat race at an Alpine lake. Cyprinids, which along with whitefish and charr constitute most of the Lake Traunsee fish community, can probably detect the boat noise at distances of nearly 400 meters. Depending on species, this distance drops in hearing generalists down to 200 (perch) and 30 m (whitefish) due to their poorer hearing abilities. Although direct observations are lacking and echo-sounder measurements were only undertaken three days after the powerboat race (and are not available to the authors), we conclude—based on the fact that main sound energies are within the best hearing range of numerous fish species and on observations reported by various authors in earlier studies—that fishes near the powerboats were disturbed by high noise levels emanating from these vessels.

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Amoser, S., and Ladich, F. (**2003**). "Diversity in noise-induced temporary hearing loss in otophysine fishes," J. Acoust. Soc. Am. **113**(4), 2170–2179.

Arveson, P. T., and Vendittis, D. J. (**2000**). "Radiated noise characteristics of a modern cargo ship," J. Acoust. Soc. Am. **107**, 118–129.

Boussard, A. (**1981**). "The reactions of roach (*Rutilus rutilus*) and rudd (*Scardinius erythrophthalmus*) to noises produced by high speed boating," Proc. 2nd Brit. Freshw. Fish. Conf., 188–200.

Chapman, C. J., and Hawkins, A. D. (**1973**). "A field study of hearing in the cod, *Gadus morhua* L.," J. Comp. Physiol. **85**, 147–167.

Enger, P. S. (**1981**). "Frequency Discrimination in Teleosts—Central or Peripheral?" in *Hearing and Sound Communication in Fishes*, edited by W. N. Tavolga, A. N. Popper, and R. R. Fay (Springer, New York), pp. 269–318.

Fay, R. R. (**1974**). "Masking of tones by noise for the goldfish (*Carassius auratus*)," J. Comp. Physiol. **87**, 708–716.

Fay, R. R. (**1988**). *Hearing in Vertebrates: A Psychophysics Databook* (Hill-Fay Associates, Winnetka, Illinois).

Fay, R. R., and Popper, A. N. (**1974**). "Acoustic stimulation of the ear of the goldfish (*Carassius auratus*)," J. Exp. Biol. **61**, 243–60.

Fernandes, P. G., Brierley, A. S., Simmonds, E. J., Millard, N. W., McPhail, S. D., Stevenson, P., and Squires, M. (**2000**). "Fish do not avoid survey vessels," Nature (London) **604**, 35–36.

Handegard, N. O., Michalsen, K., and Tjostheim, D. (**2003**). "Avoidance behavior in cod (*Gadus morhua*) to a bottom-trawling vessel," Aquat. Living Resour. **16**, 265–270.

Hawkins, A. D., and Chapman, C. J. (**1975**). "Masked auditory thresholds in the cod, *Gadus morhua* L.," J. Comp. Physiol. **103**, 209–226.

Hawkins, A. D., and Johnstone, A. D. F. (**1978**). "The hearing of the Atlantic salmon, *Salmo salar*," J. Fish Biol. **13**, 655–673.

Hawkins, A. D., and Myrberg, A. A., Jr. (**1983**). ''Hearing and sound communication under water,'' in *Bioacoustics, a comparative approach*, edited by B. Lewis (Academic, London), pp. 373–387.

Kenyon, T. N., Ladich, F., and Yan, H. Y. (**1998**). ''A comparative study of hearing ability in fishes: the auditory brainstem response approach,'' J. Comp. Physiol., A **182**, 307–318.

Ladich, F., and Popper, A. N. (**2004**). ''Parallel evolution in fish hearing organs,'' in *Evolution of the Vertebrate Auditory System*, edited by G. Manley, A. N. Popper, and R. R. Fay (Springer-Verlag, New York), pp. 95–127.

Ladich, F., and Wysocki, L. E. (**2003**). ''How does tripus extirpation affect auditory sensitivity in goldfish?'' Hear. Res. **182**, 119–129.

Ladich, F. (**1999**). ''Did auditory sensitivity and vocalization evolve independently in otophysan fishes?'' Brain Behav. Evol. **53**, 288–304.

Lesage, V., Barette, C., Kingsley, M. C. S., and Sjare, B. (**1999**). ''The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence river estuary, Canada,'' Mar. Mam. Sci. **15**, 65–84.

Malinowski, S. J., and Gloza, I. (**2002**). ''Underwater noise characteristics of small ships,'' Acta Acustica United Acustica **88**, 718–721.

Mann, D. A., Higgs, D. M., Tavolga, W. N., Souza, M. J., and Popper, A. N. (**2001**). ''Ultrasound detection by clupeiform fishes,'' J. Acoust. Soc. Am. **109**, 3048–3054.

McCauley, R. D., Fewtrell, J., and Popper, A. N. (**2003**). ''High intensity anthropogenic sound damages fish ears,'' J. Acoust. Soc. Am. **113**, 638–642.

Mitson, R. B. (**1993**). ''Underwater noise radiated by research vessels,'' ICES Mar. Sci. Symp. **196**, 147–152.

Mitson, R. B. (**1995**). ''Underwater noise of research vessels: review and recommendations,'' ICES Coop. Res. Rep. 209.

Mitson, R. B., and Knudsen, H. P. (**2003**). ''Causes and effects of underwater noise on fish abundance estimation,'' Aquat. Living Resour. **16**, 255–263.

Morgenroth, A. (**2002**). ''Verträglichkeitsprüfung zum Powerbootrennen 2002 in Lübeck–Travemünde,'' Bericht an die Class 1 Betriebsgesellschaft mbH (''Environmental impact assessment of the Powerboat race 2002 in Lübeck-Travemünde. Report to the Class 1 operating company'').

Morgenroth, A. (**2003**). ''Class 1 Championship—Powerboatrennen 2003 in Lübeck—Travemünde. Verträglichkeitsprüfung. Bericht an die Class 1 Betreiber GmbH'' (''Class 1 championship powerboat race 2003 in Lübeck—Travemünde. Environmental impact assessment. Report to the Class 1 operating company'').

Myrberg, Jr., A. A. (**1990**). ''The effects of man-made noise on the behavior of marine mammals,'' Environ. Int. **16**, 575–586.

Popper, A. N. (**1972**). ''Pure-tone auditory thresholds for the carp, *Cyprinus carpio*,'' J. Acoust. Soc. Am. **52**, 1714–1717.

Popper, A. N. (**2003**). ''Effects of anthropogenic sounds on fishes,'' Fish. Res. **28**, 24–31.

Popper, A. N., and Fay, R. R. (**1993**). ''Sound detection and processing by fish: critical review and major research questions,'' Brain Behav. Evol. **41**, 14–38.

Richardson, W. J., Greene, C. R., Malme, C. J., and Thomson, D. H. (**1995**). *Marine Mammals and Noise* (Academic, London).

Santulli, A., Modica, A., Messina, C., Ceffa, L., Curatolo, A., Rivas, G., Fabi, G., and D'Amelio, V. (**1999**). ''Biochemical responses of European Sea Bass (*Dicentrarchus labrax* L.) to the stress induced by off shore experimental seismic prospecting,'' Mar. Pollut. Bull. **38**, 1105–1114.

Scholik, A. R., and Yan, H. Y. (**2002**). ''Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*,'' Environ. Biol. Fishes **63**, 203–209.

Schummer, M. L., and Eddleman, W. R. (**2003**). ''Effects of disturbance on activity and energy budgets of migrating waterbirds in south-central Oklahoma,'' J. Wildl. Manag. **67**, 789–795.

Schwarz, A. L., and Greer, G. L. (**1984**). ''Responses of pacific herring, *Clupea harengus pallasi*, to some underwater sounds,'' Can. J. Fish. Aquat. Sci. **41**, 1183–1192.

Smith, M. E., Kane, A. S., and Popper, A. N. (**2004**). ''Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*),'' J. Exp. Biol. **207**, 427–435.

Southall, B. L., Schusterman, R. J., and Kastak, D. (**2000**). ''Masking in three pinnipeds: underwater, low-frequency critical ratios,'' J. Acoust. Soc. Am. **108**, 1322–1326.

Sverdrup, A., Kjellsby, E., Krüger, P. G., Floysand, R., Knudsen, F. R., Enger, P. S., Serck-Hanssen, G., and Helle, K. B. (**1994**). ''Effects of experimental seismic shock on vasoactivity of arteries, integrity of the vascular endothelium and on primary stress hormones of the Atlantic salmon,'' J. Fish Biol. **45**, 973–995.

Vabø, R., Olsen, K., and Huse, I. (**2002**). ''The effect of vessel avoidance of wintering Norwegian spring spawning herring,'' Fish. Res. **58**, 59–77.

Wanzenböck, J., Gassner, H., Lahnsteiner, B., Hassan, Y., Hauseder, G., Doblander, C., and Köck, G. (**2002a**). ''Ecological integrity assessment of lakes using fish communities: an example from Traunsee exposed to intensive fishing and to effluents from the soda industry,'' Water, Air, Soil Pollut. **2**, 227–248.

Wanzenböck, J., Gassner, H., Hassan, Y., Lahnsteiner, B., and Hauseder, G. (**2002b**). ''Ecology of European white fish, *Coregonus lavaretus*, in two Austrian lakes in relation to fisheries management and lake productivity,'' in *Management and Ecology of Lake and Reservoir Fisheries*, edited by Cowx, I. G. (Blackwell Science Ltd., Oxford), pp. 58–69.

Wolff, D. L. (**1967**). ''Das Hörvermögen des Flußbarsches (*Perca fluviatilis* L.)'' (''The hearing ability of the European perch (*Perca fluviatilis* L.)''), Biol. Zentralbl. **86**, 449–460.

Wolff, D. L. (**1968**). ''Das Hörvermögen des Kaulbarsches (*Acerina cernua* L.) und des Zanders (*Lucioperca sandra* Cuv. und Val.)'' (''The hearing ability of the ruffe (*Acerina cernua* L.) and the pike perch (*Lucioperca sandra* Cuv. und Val.)''), Z. Vergl. Physiol. **60**, 14–33.

Wysocki, L. E., and Ladich, F. (**2002**). ''Can fishes resolve temporal characteristics of sounds? New insights using auditory brainstem responses,'' Hear. Res. **169**, 36–46.

Wysocki, L. E., and Ladich, F. (**2003**). ''The representation of conspecific sounds in the auditory brainstem of teleost fishes,'' J. Exp. Biol. **206**, 2229–2240.

Wysocki, L. E., Ladich, F., and Dittami, J. (**2004**). ''Noise, stress, and cortisol secretion in teleost fishes,'' Horm. Behav. **46**, 125.

Wysocki, L. E., and Ladich, F. ''Hearing in fishes under noise conditions'' J. Assoc. Res. Otolaryngol. (in press).

Yost, W. A. (**2000**). *Fundamentals of Hearing—An Introduction* (Academic, San Diego).