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Year-round variability of ambient noise in temperate freshwater habitats and its implications for fishes

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Abstract

Changes in habitat acoustics over the year can potentially affect fish hearing and orientation to sound, especially in temperate climates. This is the first study where year-round changes in ambient noise in aquatic habitats were assessed. Seven different European fresh-water habitats were chosen for this study. Sound pressure level (SPL) and spectral composition of the ambient noise varied in both quiet stagnant habitats (lakes, backwaters) and in flowing habitats (streams, rivers). Linear equivalent SPL ($L_{Leq, 60s}$) tended to be lower in stagnant habitats (means: 91.6–111.7 dB) than in flowing habitats (means: 111.2–133.4 dB). The changes in SPL were smallest in the river (means: 4.2–4.4 dB, maxima: 8.5–10.1 dB), whereas significantly higher values were measured in stagnant habitats and the stream (means: 9.9–14.9 dB, maxima: 25.1–30.9 dB). The spectral compositions of the ambient noise determined at different times of the year were highly correlated to each other at the river sites (mean cross-correlation coefficients: 0.85 and 0.94) and were weaker or not correlated at the other study sites (means: 0.24–0.76). The changes in ambient noise spectra were negatively correlated to changes in SPL, indicating that large changes in SPLs were accompanied by large changes in spectral composition and vice versa. Comparison of these ecoacoustical data with a preceding study (Amoser and Ladich in *J Exp Biol* 208:3533–3542, 2005) indicates that the auditory sensitivity in hearing specialists is affected by changes in ambient noise levels and spectra throughout a year and that this effect tends to be more pronounced in stagnant waters and the stream than at river sites. On the other hand, absolute noise levels result in a higher degree of masking in flowing waters.

Keywords

Ambient noise; Sound pressure levels and spectra; Freshwaters; Fish; Masking

Introduction

Terrestrial and aquatic habitats have background noise (ambient or habitat noise, soundscape; Fay 2009) composed of biotic sounds from con- and heterospecifics, including prey and predators, and also abiotic sounds generated by water flow, wind, waves, precipitation and surf. Sound is transmitted at much higher speed and only marginally absorbed in water compared with air. It can therefore propagate over long distances,

depending on water depth and sound frequency, and is an important signal carrier for fish and other aquatic animals (Hawkins and Myrberg 1983; Bradbury and Vehrencamp 1998; Mann 2006). In the past decades, noise of anthropogenic origin has continuously increased (Croll et al. 2001; Andrew et al. 2002). In aquatic habitats, anthropogenic noise arises from shipping, geophysical surveys, power plants and other industrial activities (Greene 1995; Scholik and Yan 2001, 2002a, 2002b; Popper 2003; Vasconcelos et al. 2007). Our knowledge about ambient noise mainly pertains to the marine ecosystem (e.g. Wenz 1962; Cato 1976; Urlick 1983; McConnell et al. 1992; Tolimieri et al. 2004; Egner and Mann 2005; Samuel et al. 2005; McDonald et al. 2006; Codarin et al. 2009). By contrast, data from freshwater habitats are limited (Bom 1969; Boussard 1981; Lugli and Fine 2003, 2007; Lugli et al. 2003; Amoser et al. 2004; Amoser and Ladich 2005; Wysocki et al. 2007). In freshwaters, ambient noise levels tend to be lower in standing than in fast-flowing habitats (lakes and backwaters vs. streams and rivers) (Amoser and Ladich 2005; Wysocki et al. 2007). In two preceding studies, we showed that spectral noise levels differed by more than 40 dB between habitats (e.g. a lake and a river) in spring and early summer (Amoser and Ladich 2005; Wysocki et al. 2007). This resulted in pronounced differences in the degree of masking in hearing specialists and in minor effects in non-specialists (Amoser and Ladich 2005).

Seasonal changes in the soundscape of fish habitats have not been studied so far. The ambient noise in freshwater habitats can vary in the course of a year because of changes in transported water volume, flow velocity, water turbulence and the (acoustic) activity of aquatic organisms (Tonolla et al. 2009). Apart from one study assessing changes in the ambient and anthropogenic noise in a coastal sea turtle habitat in the course of a summer (Samuel et al. 2005), we know of no study looking at year-round changes in the acoustical environment of fishes.

The aim of this study was to describe year-round changes in the levels and spectral composition of ambient noise (soundscape) in seven freshwater habitats representing a variety of freshwaters in Central Europe and to assess their masking effect on fishes based on the preceding study (Amoser and Ladich 2005). These results will provide a first insight into the challenges fishes have to cope with in the course of a year in natural habitats.

Materials and methods

Study sites

In a preceding study (Wysocki et al. 2007), 12 different aquatic habitats throughout Austria were described with regard to their ambient noise characteristics in spring and early summer (for water depths and further details on aquatic habitats investigated see Table 1 in Wysocki et al. 2007). Out of these, seven sites were chosen (near Vienna, Austria) that represented the variety of aquatic habitats and the variety of acoustical environments in this region. These comprised stagnant or slow flowing freshwater habitats (lakes and river backwaters) as well as fast-flowing freshwaters (a small streamlet and the large Danube River) (Fig. 1).

Among the stagnant habitats, two different types of lakes were chosen, Lake Lunz (LL) representing typical deep alpine mountain lakes, and Lake Neusiedl (LN) representing a flat lowland lake, and two backwaters of the Danube River, the “Gänsehaufen Traverse” (BG) and the “Schönauer Traverse” (BS). Among fast-flowing habitats, the Triesting stream (ST) and the Danube River were chosen. The study sites were the Danube River at Orth (RDO) that was situated in a free-flowing area and the second in a retained part of the river (Danube River near Danube Island, RDI).

The recordings and noise measurements were made at the same spot within each habitat every 2 months (on average every 72 days) throughout the course of a year from late June 2004 to late June 2005. The exception was Lake Neusiedl, where one noise recording (January 2005), but not the noise level, is missing. We decided to measure just at one sampling site per habitat and concentrate on a wide spectrum of habitats, although by doing this the potential variation within each habitat might be underestimated. However, dealing with this variability would have gone beyond the scope of this study.

Ambient noise recordings, sound pressure level measurements and analysis

Noise measurements and recordings followed the protocol given by Wysocki et al. (2007). All sound pressure levels (SPL) are given in dB re 1 μPa . Note that SPL ($L_{\text{Leq}, 60\text{s}}$) measured by the sound level meter (Fig. 2, Table 1) are RMS values determined for a frequency range of 5–20 kHz, whereas spectral SPLs shown in Fig. 3 were calculated using a filter bandwidth of 1 Hz.

Ambient noise was recorded on a DAT-Rekorder (Sony TCD 100, Sony Corporation, Tokyo, Japan) at a sampling rate of 44.1 kHz using a hydrophone (Brüel and Kjaer 8101, Naerum, Denmark; frequency range: 1–80 kHz $\pm$ 2 dB; voltage sensitivity: -184 dB re 1 V μPa^{-1}) connected to a power supply (Brüel and Kjaer 2804). Recordings varied from 1 to 3 min. To provide constant recording conditions, the hydrophone was kept at depths between 0.3 and 1.0 m due to the very shallow water conditions at many of the recording sites (e.g. BG, BS, ST, RDI).

Immediately before and after each noise recording, the broadband SPL of the ambient noise was measured for 1 min using a sound level meter (Brüel and Kjaer 2238 Mediator), a power supply, and a Brüel and Kjaer 8101 hydrophone. It was therefore possible to attribute SPL values to each of the tape recordings. The equivalent continuous SPL (L_{Leq}), averaged over 60 s (Linear [L] or flat weighting, 5–20 kHz) was obtained. The L_{Leq} is a measure of the averaged energy in a varying sound field and is commonly used to assess environmental noise (ISO 1996 2003).

Noise was analyzed using STX 3.7.4, a sound analyzing software developed by the Institute of Sound Research at the Austrian Academy of Sciences in Vienna. Relative FFT amplitude spectra of 60 s noise samples were calculated (filter bandwidth 1 Hz, overlap 50%, window: Blackman–Harris). Then, absolute spectra were calculated using the averaged L_{Leq} value from the noise level measurements before and after each ambient noise recording, following the algorithm described in Amoser et al. (2004) and Wysocki and Ladich (2005).

Statistical analysis

To assess differences in absolute SPLs as well as changes between months, the mean $L_{\text{Leq}, 60\text{s}}$ was calculated for each habitat and measuring day (Table 1). Furthermore, to determine changes in the $L_{\text{Leq}, 60\text{s}}$ throughout a year in each habitat, the differences between each of the six measuring days were calculated and averaged (6 measuring days resulted in 15 differences). One-way analysis of variance (ANOVA) was applied to assess differences between habitats in absolute SPLs, whereas one-way ANOVA with replications was calculated to determine the differences between habitats in the relative changes in SPLs throughout a year. LSD-adjusted, pairwise multiple comparisons followed every ANOVA to assess specific differences between noise conditions. The P level was set at 0.05.

To determine year-round variations in the spectral composition of the ambient noise within each site, cross-correlation coefficients were computed using STX 3.7.4. Sixty-second noise samples of each habitat and recording month (June 2004 to June 2005) were chosen. We then cross-correlated the noise spectrum of each recording date with all other recording

dates within one habitat ($n = 15$, except for LN where $n = 10$). Cross-correlation values from 1 to 0.9 indicated a strong correlation, values from 0.9 to 0.6 a weak, and values from 0.6 to 0 no correlation (Townend 2002).

Cross-correlation coefficients are simply a measure for similarity in shape, i.e. spectral composition, without considering the absolute noise levels (Wood et al. 2005). In order to reliably assess a potential masking effect of the noise, this information must be combined with overall absolute SPLs. Accordingly, a low SPL most probably means a low degree of masking, independent of the correlation coefficient.

Parametric statistical tests were applied because the data showed normal distributions and homogeneity of variances. All statistical tests (except cross-correlations) were run using SPSS version 12.0. The cross-correlation coefficients were calculated using the sound analyzing software STX 3.7.4.

Results

Ambient noise levels

The SPL ($L_{Leq, 60s}$) values encountered in the investigated freshwaters ranged from 76.9 dB in a backwater of the Danube River (BG) to 137.8 dB in the main channel of the Danube River (RDO) (Figs. 1, 2a, Table 1). The mean noise level ($L_{Leq, 60s}$) in the Danube River (free-flowing area, RDO) was 133.4 dB, whereas the Triesting stream (ST) and the Danube River at the Danube Island (RDI) site were not as noisy, with mean noise levels being 112.2 and 111.2 dB, respectively. In stagnant habitats, mean noise levels were normally below 110 dB (BG, BS, LL), with Lake Neusiedl (LN) being an exception (111.6) (One-way ANOVA, $F_{6, 35} = 19.12$, $P < 0.001$) (Fig. 2a).

Maximum differences in SPLs ($L_{Leq, 60s}$) between months ranged from 8.5–10.1 dB at the River Danube sites (RDO and RDI, respectively) to 25.1–27.9 dB in the stagnant habitats and to 30.9 dB in the Triesting stream (ST). Significant differences were found between habitats (One-way ANOVA, $F_{3, 38, 47.26} = 5.37$, $P < 0.01$). Mean differences were lowest in the Danube River and ranged from 4.2 dB in the Danube River at the Danube Island (RDI) to 14.9 dB in the Triesting stream (ST) (Fig. 2b, Table 1). The differences at the Danube River sites were significantly lower than those at all other sites (Triesting stream and all stagnant habitats).

Ambient noise spectra

The spectral composition of the ambient noise revealed major differences between habitats (Fig. 3). The spectra of fast-flowing waters showed a notch below 1 kHz (150–800 Hz), which is clearly evident in the Danube River (Fig. 3, RDO and RDI) and to a lesser degree in the Triesting stream (Fig. 3, ST). Stagnant habitats all had high noise levels at frequencies below 500 Hz and then tended to be rather flat (Fig. 3).

The Danube River showed very similar spectral profiles over the year, with a variation in spectral levels of 15.2 dB (RDO at 3.1 kHz) and 26.8 dB (RDI at 760 Hz) (Fig. 3). The levels varied more in all the other habitats: range in BG: 35.8 dB (5 kHz), BS: 46.2 dB (5 kHz), LL 37.9 dB (680 Hz), LN: 33.8 dB (570 Hz) and ST: 50.7 dB (660 Hz) (Fig. 3, BG–ST). This result was supported by the cross-correlation coefficients, which are measures of the similarity between the shape of the amplitude spectra within each habitat (Fig. 4). Again, the Danube River showed the highest mean cross-correlation coefficients ($r = 0.85$ and 0.94 , RDI and RDO, respectively), whereas the Triesting stream (ST) had the lowest mean cross-correlation coefficient ($r = 0.24$). Significant overall differences in the cross-correlation coefficients between habitats were found (One-way ANOVA: $F_{6, 93} = 16.8$, $P < 0.001$).

Subsequent LSD post-hoc testing revealed that the two Danube River sites (RDI, RDO) differed significantly from all the other sites (except BG) (Fig. 4).

The mean cross-correlation coefficients were negatively correlated with the mean change in SPLs ($r = -0.807$, $n = 7$, $P < 0.05$), which means that large changes in SPLs between months were accompanied by large changes in the spectral composition (low cross-correlation values) of the ambient noise and vice versa.

Discussion

Variability of ambient noise throughout the year

The present study is the first one investigating the changes in ambient noise in aquatic habitats in a period of one year. The influence of changes in ambient noise in the course of a year on sound detection in fishes has never been assessed before. The ambient noise of the seven freshwater habitats determined in this study showed some clear differences regarding the prevailing broadband noise levels and their frequency distribution. Both the SPLs and spectral composition changed throughout the year in all temperate freshwater habitats studied, but no changes clearly attributable to season could be recognized. Flowing waters are commonly noisier than standing ones and changes were more pronounced in stagnant waters and in the stream than at the river sites investigated.

The Danube River (free-flowing and retained study site) showed both the highest and most constant SPLs and spectral composition; this was shown by very high cross-correlation coefficients, indicating a strong consistency in spectral composition. The Triesting stream, on the other hand, showed the highest variability both in SPLs (91–125 dB) and spectral composition (low correlation coefficients). These differences may be attributable to differences in substrate types (RDO: cobble, ST: boulders and cobble, after Yamazaki et al. 2006), water volume transported and in current velocities (RDO: $1\text{--}3\text{ m s}^{-1}$, ST: $>0.3\text{ m s}^{-1}$). Furthermore, the Triesting stream is probably more susceptible to changes in water volume due to heavy rainfall or snow melt, explaining the high variability in noise levels and spectra.

The other freshwater habitats were also rather variable and showed no clear seasonal trend. This also held true for very similar habitats like the two Danube backwaters [“Gänsehaufen Traverse” (BG) and “Schönauer Traverse” (BS)]. Interestingly, the higher activity of aquatic insects during summer did not influence the overall noise levels measured in July and August, whereas higher spectral noise levels were detected around 6 kHz, consistent with data of Aiken (1982). These frequencies are outside the hearing range of most native freshwater fishes, and we therefore neglected this phenomenon in further analysis. The two lakes showed great dissimilarities, reflecting their different characters: Lake Lunz is a typical, small deep Alpine lake, Lake Neusiedl a very large and shallow steppe lake, and thus potentially more susceptible to wind- and wave-generated noise. Regarding the spectral composition, all standing habitats showed a high variability throughout the year and no seasonal patterns were recognizable.

How can the variability within certain habitats throughout a year be explained? No single factor such as snow melt in spring or aquatic insects in summer can explain differences between months (but see next paragraph). Neither overall SPLs nor spectral levels increased pronouncely in April versus the other months. Similarly, aquatic insects do not substantially contribute to higher noise levels in early summer in the frequency range below 5 kHz used by fishes. Tonolla et al. (2009) showed that the SPLs and sound signatures in running waters depend highly on the water velocity and flow obstructions. We therefore conclude that different combinations of factors such as snow melt, water flow, bottom substrate

transportation, wind and surf, animal sounds and anthropogenic sound (at the site RDI) cause this variety. Fish have to cope with this over the year, independent of season. Factors such as precipitation or ice movement, which did not occur during our measurements, will also influence the auditory scene of fishes.

The variation of ambient noise during the course of a year, from one season to another or even within shorter periods of time (days), has been almost totally neglected so far despite its relevance for acoustic orientation and communication in fishes. Samuel et al. (2005) assessed the ambient noise in the Peconic Bay estuary system in Long Island, New York, with respect to juvenile sea turtles and human activities and found increased noise levels (up to 26 dB) during the period of highest human activity. However, they did not assess over a whole year (recording period: July to September 2001) and were only interested in a possible human impact on sea turtles in these waters.

Present results, namely the lack of a seasonal change, may be typical for temperate freshwater habitats. Despite the lack of data from other parts of the world, it is assumed that freshwater habitats in tropical regions, which are characterized by heavy rainfall for a long time and pronounced changes in water level, may reveal opposite trends, namely seasonal changes in SPL and spectra. In which way rainy seasons influence the soundscape needs to be investigated.

Possible influence of ambient noise on fishes

To what degree do ecological constraints like noise influence acoustic orientation and communication in fishes? According to our one-year data, SPLs within particular habitats could vary up to approximately 40 dB, without revealing a particular seasonal pattern, in the best hearing range of hearing specialists such as the carp (300–1,000 Hz). This potentially causes masking effects of up to 40 dB based on our knowledge from a preceding study (Amoser and Ladich 2005). In that study, we investigated the effects of natural ambient noise on the auditory sensitivity of fishes with different auditory capabilities, the common carp and the European perch, similar to the present study. We were able to show that the carp's hearing thresholds were masked by 49 and 30 dB under high Danube River and moderately high Triesting stream noise levels, respectively, whereas the degree of masking at the lower noise levels in a lake and a backwater of the Danube River were around or even below 10 dB. High noise amplitudes certainly decrease the carp's ability to detect sounds of low level and their temporal patterns emanating from conspecifics, heterospecifics such as predators or prey objects and abiotic sources. Combining this knowledge with the ambient noise data of the present paper indicates that hearing specialists may have to deal with an ever-changing masking effect not only when migrating from one habitat to the other, but also within the same habitat over the year, depending mostly on hydrology (e.g. volume and speed of water flow, turbulence, sediment transport) and to a lesser extent on biotic sources (such as water insects).

Physically generated sound may constitute a local phenomenon especially in shallow waters (such as at our study sites LN and ST) where the cutoff phenomenon limits the propagation of low frequency sounds. This phenomenon explains to some extent the “noise window” of relative low noise levels in the 100–300 Hz region at our study sites RDI and RDO. A similar low energy “noise window” were described by Lugli and Fine (2003, 2007) in the shallow stony streams they investigated.

High frequency sound may travel over longer distances and this may have been a driving force in the evolution of sensory systems. High frequency hearing, and thus the extension of the distances over which freshwater fish are able to communicate and orient acoustically,

may have been a key factor in the evolution of hearing specializations (Ladich 2000; Ladich and Popper 2004).

Besides masking, ambient noise may also be an important cue for acoustical orientation throughout a year. Several studies in marine environments showed that fish of different stages orient towards coral reef sound and thus may be able to detect suitable habitats (Leis et al. 2002, 2003; Tolimieri et al. 2000, 2004; Simpson et al. 2008). It needs to be explored if the soundscape in freshwaters serves as a cue for finding particular habitats similar to the situation in marine environments.

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Fig. 1.

Map of Austria showing the Austrian freshwaters and a detailed map (*inset*) showing the location of the seven study sites. In alphabetical order: *BG* backwater Gänsehaufen Traverse, *BS* back-water Schönaauer Traverse, *LL* Lake Lunz, *LN* Lake Neusiedl, *RDO* Danube River at Orth, *RDI* Danube River at Danube Island, *ST* Triesting stream. Map of the Austrian Federal Ministry for Agriculture, Forestry, Environment and Water Management © BMLFUW 1998–2004

Fig. 2.

Mean ($\pm$ SE) sound pressure level ($L_{Leq, 60s}$) (**a**) and mean ($\pm$ SE) differences (**b**) between different months for all seven habitats. Non-significant differences between habitats are indicated by the same lower case letters (LSD post-hoc test). For abbreviations see Fig. 1

Fig. 3.

Ambient noise spectra of the seven habitats investigated. *Colours* indicate measurements at different dates. *Red* June 2004, *Orange* August 2004, *Brown* October 2004, *Blue* January 2005, *Green* April 2005, *Pink* June 2005. For abbreviations see Fig. 1. Frequency range 20–5 kHz, filter bandwidth 1 Hz, Blackman Window, 50% overlap

Fig. 4. Mean ($\pm$ SE) cross-correlation coefficients within seven habitats. Non-significant differences between habitats are indicated by the same lower case letters. For abbreviations see Fig. 1

Table 1

Mean equivalent continuous SPL ($L_{Leq, 60s}$) measured in seven habitats throughout the year. The value in the last column (Differ.) represents the mean difference between SPLs ($L_{Leq, 60s}$)

Habitat		June 04	Aug 04	Oct 04	Jan 05	Apr 05	June 05	Differ.
LL	L_{Leq} mean	86.3	105.5	92.2	91.2	92.1	79.6	9.9
LN	L_{Leq} mean	96.7	104.5	114.6	121.8	111.8	120.3	11.7
BS	L_{Leq} mean	97.5	89.4	106.7	92.2	78.8	94.9	11.1
BG	L_{Leq} mean	103.5	86	90.8	94.3	76.9	101.2	12.1
ST	L_{Leq} mean	102.7	112.5	124.6	115.6	93.7	124.5	14.9
RDI	L_{Leq} mean	112	104.7	113.4	114.8	113.2	109.5	4.2
RDO	L_{Leq} mean	135.2	129.3	131	130.3	136.8	137.8	4.4

All levels are given in dB re 1 μ Pa

BG backwater "Gänsehaufen Traverse", *BS* backwater "Schönauer Traverse", *LL* Lake Lunz, *LN* Lake Neusiedl, *RDO* Danube River at Orth, *RDI* River Danube at Danube Island, *ST* Triesting stream