Summary

I start by presenting the work already done on metadata, audio player and media library. Then I discuss the chosen approach for mixing animal sounds and anthropogenic noises, and discuss the effect of distance on sound propagation in seawater. I then discuss standard and novel ways of visualizing the results.

Current mixer concept (will be animated of course). Noise sources can be switched on and off interactively, several at a time. Playback mixes animal calls and anthropogenic noises and soundscapes, simulating the animals' perception of the noises (through “filtering ” and "masking", explained below). A choice between several animals is possible, one animal at a time (use the “zoom” menu in the toolbar to enlarge).

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Requirements and assumptions

Research on underwater noises and their effect on marine life is a complex subject. The underlying assumption of this work package is that a visualization of real-time acoustic analysis in combination with sound playback can convey more information and do so more effectively, than a sound file alone, specially when multiple sound sources are involved [Ferguson, Moere, Cabrera, 2005].

The information platform is meant to reach out to an audience of laypersons. The funding institution has specifically requested to address an audience of (young) adults, not of children, therefore we assume a knowledge level equivalent to at least secondary education (German: 10. Klasse), which includes mathematical modelling and diagramming of real-life processes, oscillating systems and waves [LISUM, 2017]. These concepts are assumed to be understood by the audience, and need not be explained. Nevertheless, the visualizations need to be easy to grasp without assuming previous knowledge of standard scientific audio representations, therefore we should look beyond an audio measurement approach, e.g. spectrograms, audiograms, waveforms. New forms of visualizations need to be researched.

The platform shall enable end-users to listen to, and interact with recordings of animal sounds and of underwater noises. The visualization needs to include interactive elements that enable the audience to explore the sounds, to combine or overlap selected recordings. A balance needs to be found between interactivity and ease of use, e.g. by clearly demarcating interactive elements from the main visualization area.

The perception of underwater noises by specific sea animals will be visualized. Therefore, sounds as they are heard by animals will be visualized, focusing on animal perception and not on human perception. This change of perspective is made necessary by the message we are trying to convey. Different approaches to realize this are discussed hereafter.

Metadata

A necessary step to meet the requirements listed in the first paragraph is to have at our disposition a collection of underwater recordings with sufficiently informative metadata. For this purpose, an ontology for describing field recordings and animal sounds (login required) was developed (fig. 1).

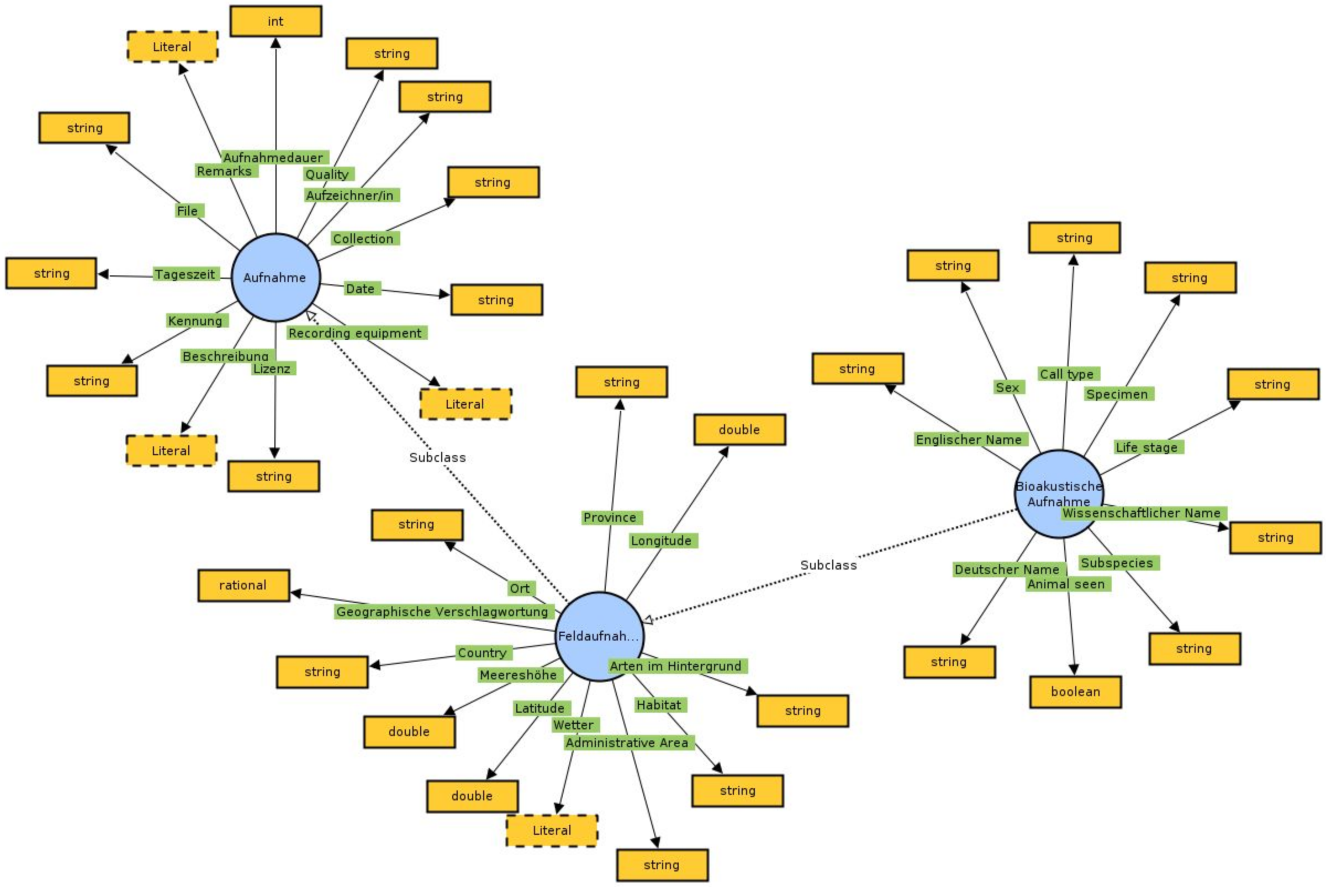

Fig. 1: Ontology for describing field recordings and animal sounds (use the “zoom” menu in the toolbar to enlarge)

The ontology was (partially) implemented in the information platform as controlled vocabularies, input forms, media types, and database views. Perspectively, the ontology will enable the integration of the data into the media repository of MfN to ensure its long-term availability.

Controlled vocabularies:

- License (Lizenz): a list of accepted media licenses (e.g. CC-BY-SA etc.)
- Noise sources (Lärmquelle): an expandable list of various biotic, anthropogenic and abiotic noise sources (e.g. earthquake, sonar).
- Ocean or sea (stored in the field "Geographische Verschlagwortung"): A list of world oceans and seas.

Input forms and media types:

- Animal sound (Bioakustische Aufnahme): intended for documenting recordings of animal vocalizations (scientific name of the species, German/English name, recordist, date, license, playback speed, etc.)

- Field recording (Feldaufnahme): intended for documenting soundscapes and recordings of abiotic or anthropogenic noises (noise source, recordist, data, playback speed, etc)

Views:

Two kinds of views allow for simple playback of the audio recordings on the information platform. These views use standardized audio diagrams, such as spectrograms and waveform diagrams. These views allow for browsing, grouping and sorting of the recordings using metadata, thus providing a low-level exploratory access to the audio recordings in the form of a browsable media library (fig. 2).

- Single recording view: each recording is identified by a unique URL, showing the recording and its metadata
- Media library view: recordings aggregated by ocean, noise source or species

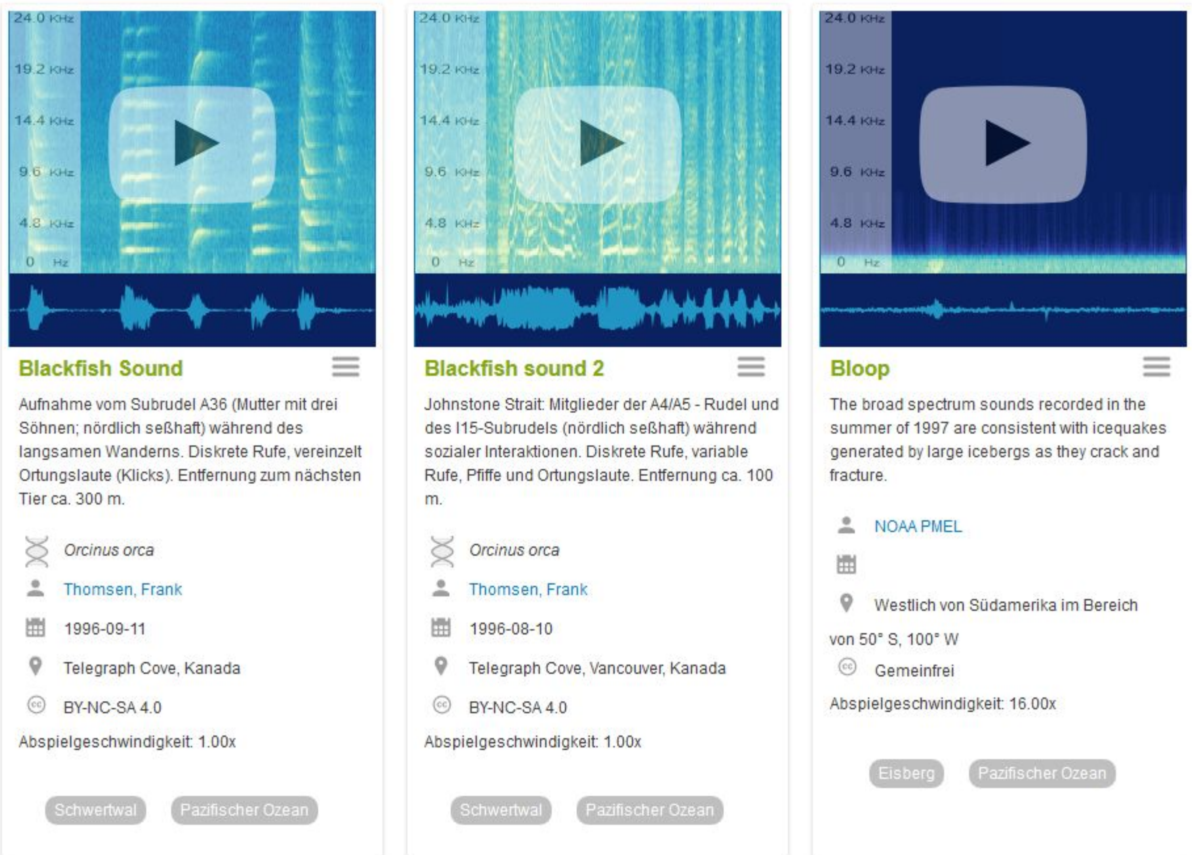

*Figure 2: (Partial) results of an audio search for the keyword "Pazifischer Ozean" on the information platform. Note that **these are not visualizations**, just an additional way of exploring the metadata (use the "zoom" menu in the toolbar to enlarge)*

Acoustic concept

The acoustic concept reflects the requirements documented in the project proposal: an adult lay person shall be able to experience underwater soundscapes and noise pollution from the perspective of selected marine animals.

The effect of noise pollution on the hearing capabilities of marine animals has been studied from the point-of-view of absolute hearing sensitivity, critical bandwidths and duration of acoustic signals [Erbe et al., 2016].

Another important aspect is that of sound propagation effects, which influence the acoustic properties of a sound as perceived at a distance, and may help to explain why marine mammals sometimes collide with loud ships [Gerstein, 2002]. This is discussed further down under “sound propagation effects”.

An additional assumption is provided by the "allotonic frequency hypothesis", which states that the hearing range of an animal is not necessarily the same as its vocalization range, but is also determined by predator-prey relationships. This hypothesis has been particularly studied for the interaction between bats and moths [Spangler, 1988]. The same phenomenon has been demonstrated for porpoises and orcas: porpoises can hear orcas, but the frequencies used by porpoises for echolocation are above the hearing range of orcas [Kyhn et al., 2013].

A technical aspect that merits consideration is that underwater noises are usually recorded with a sampling rate of 44 or 48 kHz. This includes recordings captured by hydrophone arrays used for acoustic monitoring (see Uta et al., 2004 for a description of such a setup). Such recordings can capture frequencies up to 24 kHz (Nyquist–Shannon sampling theorem).

Simulation of the perception of underwater noises by selected marine animals through **filtering**

Simulating the perception of underwater noises by marine animals entails examining the hearing capabilities of these animals and filtering out the regions of the frequency spectrum outside of the hearing range of the animal. Biological, physical and technical aspects of underwater acoustics have to be taken into consideration in order to examine the feasibility of the mixer application in relation to the hearing capabilities of chosen species of marine animals (fig. 3).

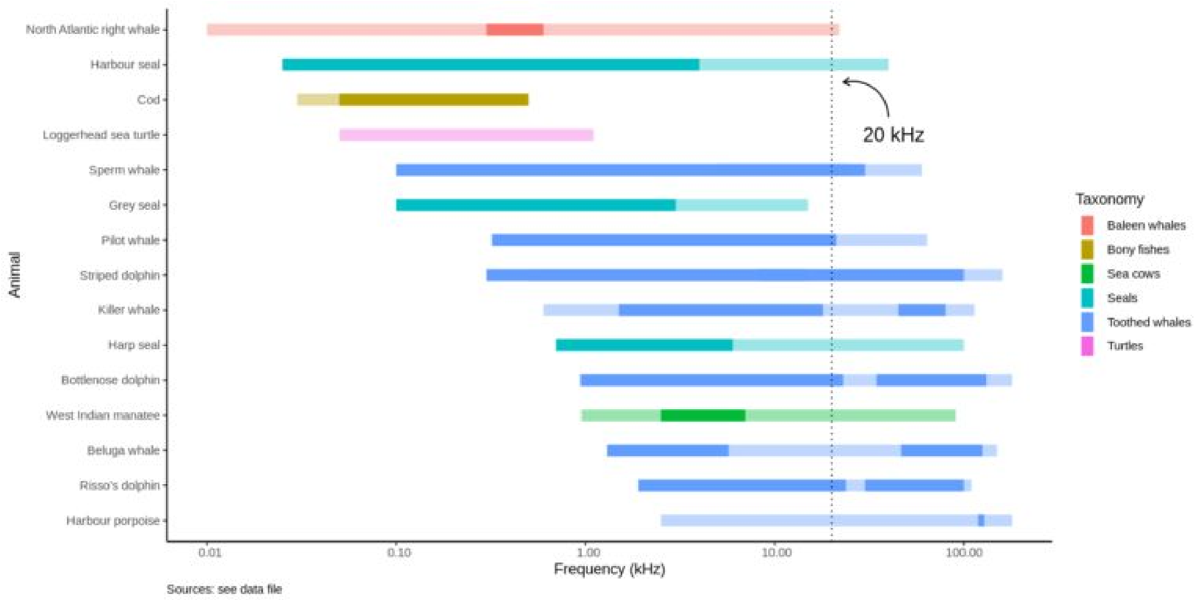

Figure 3: Hearing and vocalization ranges for marine animals, includes clicks for cetaceans (use the "zoom" menu in the toolbar to enlarge). See Appendix A for sources.

Cetaceans

The hearing range of baleen whales is largely unknown. However, the hearing range of North Atlantic right whales (*Eubalaena glacialis*) has been estimated to range from 10 Hz up to 22kHz, based upon modeling of the whale's hearing apparatus [Parks et al., 2007]. Therefore, the full range of frequencies heard by right whales is captured by most recordings of anthropogenic noise.

The hearing range of toothed whales varies considerably between species. However, with the probable exception of sperm whales and pilot whales, the range of frequencies heard by most toothed whales is not captured in most recordings of anthropogenic noise.

Pinnipeds

The hearing range of harbour seals (*Phoca vitulina*) is best between 6 kHz to 12 kHz [Wolski et al., 2003] but seals can hear up to 40 kHz underwater [Reichmuth et al., 2013]. The hearing range of grey seals (*Halichoerus grypus*) is fully captured in available recordings. The hearing range of harbour seals (*Phoca vitulina*) and harp seals (*Pagophilus groenlandicus*) is partially captured by most recordings of anthropogenic noise.

Sea cows

The peak auditive sensitivity of the West Indian manatee (*Trichechus manatus latirostris*) extends from 8 kHz to 32 kHz, the full hearing range spans 950Hz to 90.5 kHz [Gaspard, 2012]. The hearing range of sea cows is partially captured by most recordings of anthropogenic noise.

Fishes

The greatest hearing sensitivity of the cod (*Gadus morhua*) is in the range 60 to 310 Hz [Chapman & Hawkins, 1973]. The hearing range of cod is fully captured by most recordings of anthropogenic noise.

Sea turtles

The hearing range of loggerhead sea turtles (*Caretta caretta*) is 50 Hz to 1100 Hz and the highest sensitivity is between 100 Hz and 400 Hz [Lavender, Bartol & Bartol, 2014]. The hearing range of loggerhead sea turtles is fully captured by most recordings of anthropogenic noise. However, to my knowledge, turtles do not produce any sound.

Simulating the disruption in acoustic communication through **masking**

The goal of this approach is to simulate the disruption in the acoustic communication of selected animals.

This method mixes the animal vocalization and the anthropogenic noise after applying a filter to the noise. The resulting mix is then brought into the *human hearing range* for playback.

As different taxa of marine mammals vocalize over a frequency range that is much wider than the range of human hearing (fig. 3), the range has to be compressed. The vocalization range of marine mammals ranges from 9 Hz (Blue whale) to 150 kHz (Dolphins and Porpoises). The human hearing range is 20 Hz to 18 kHz [Suzuki, 2003]. For each species, a conversion factor will have to be estimated, to bring the animal vocalizations into the human hearing range.

Sound propagation effects

Sound propagation in seawater, specifically its masking potential, is affected mainly by three distance-related effects (Erbe et al., 2016):

- The spectrum of sound is dampened as a function of distance, as higher frequencies are absorbed more rapidly than lower frequencies.
- Sound reflections at the water surface and at the sea bottom result in interference phenomena which can change the frequency spectrum of the perceived noise. This phenomenon (Lloyd Mirror effect) is particularly present at short distances (e.g. passing ships).
- Frequency dispersion affects the spectral and temporal structure of perceived sounds, resulting in stretched sounds at several km distance.

It is unlikely that we can obtain a sufficient number of noise recordings at different distances. To increase the range of sounds in the application, a Jupyter notebook was set up to investigate suitable sound processing algorithms to simulate the sound characteristics of underwater noises at different distances.

Preliminary conclusion*: Absorption and interference can be simulated using off-the-shelf filters, but available dispersion filters do not render sounds similar to those that can be heard in the ocean. Simulating dispersion would thus require the development of a custom filter.*

See Siebert et al. (2014) Appendix B for clues on frequency dispersion phenomena.

Conclusion

The filtering and masking approach has tremendous potential to support a narrative on ocean noise pollution in the context of the information platform. The effects of anthropogenic noises on animal communication should be easy to grasp for a layperson, however, the range of possible animal / noise combinations is limited by technical factors.

Visual representations of sound

There are many standard and non-standard possibilities for visualizing sound. Standard visualizations include particularly spectrograms and waveform diagrams.

Volume meter

Sound volume is used to describe the subjective impression of the listener, as opposed to loudness, amplitude, intensity, dynamics etc., which measure quantifiable physical parameters. An approximate indication of sound volume can therefore be used to relate the underwater noise to the listener's own experience by comparing the underwater noise to known loud noises, like jet engines, loud music, jackhammer…

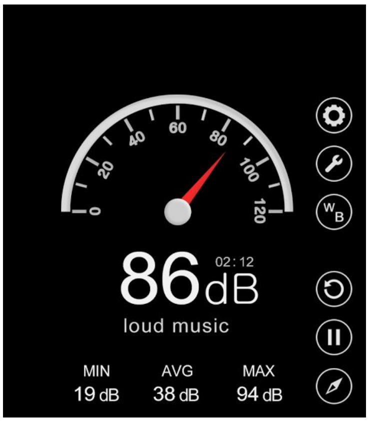

Fig 4: a simple "volume gauge"

Spectrograms

Spectrograms of the above examples demonstrate that a spectrogram of the sound is not informative at all in this context (fig 5, 6). For the orca vs. sonar example, although the sonar is clearly visible, orca vocalizations are visually indistinguishable from background noise for a layperson. Therefore a spectrogram is by itself not easily interpretable by a layperson. However, the idea that a spectrogram becomes understandable when used in conjunction with synchronized audio was put forward, and will be evaluated.

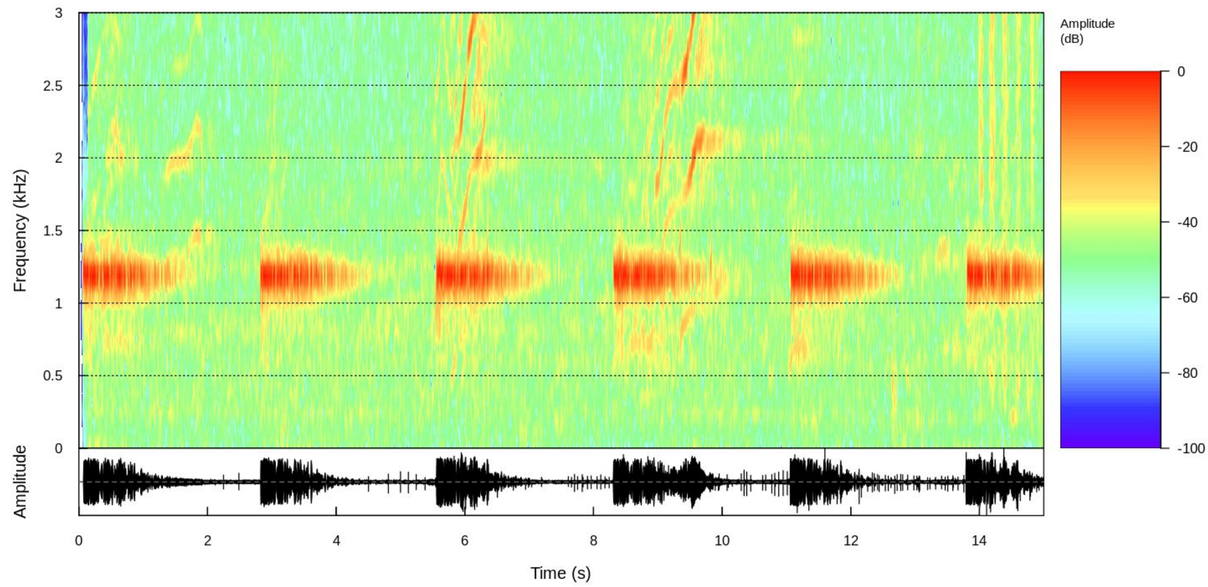

Fig. 5: Spectrogram of orca and sonar

For the whale vs. ship example, a spectrogram of the sound is not informative either (fig. 5), at least not by itself, as the sounds are too low to be told apart visually. Here again, the possibility of syncing a sound and a spectrogram will be evaluated.

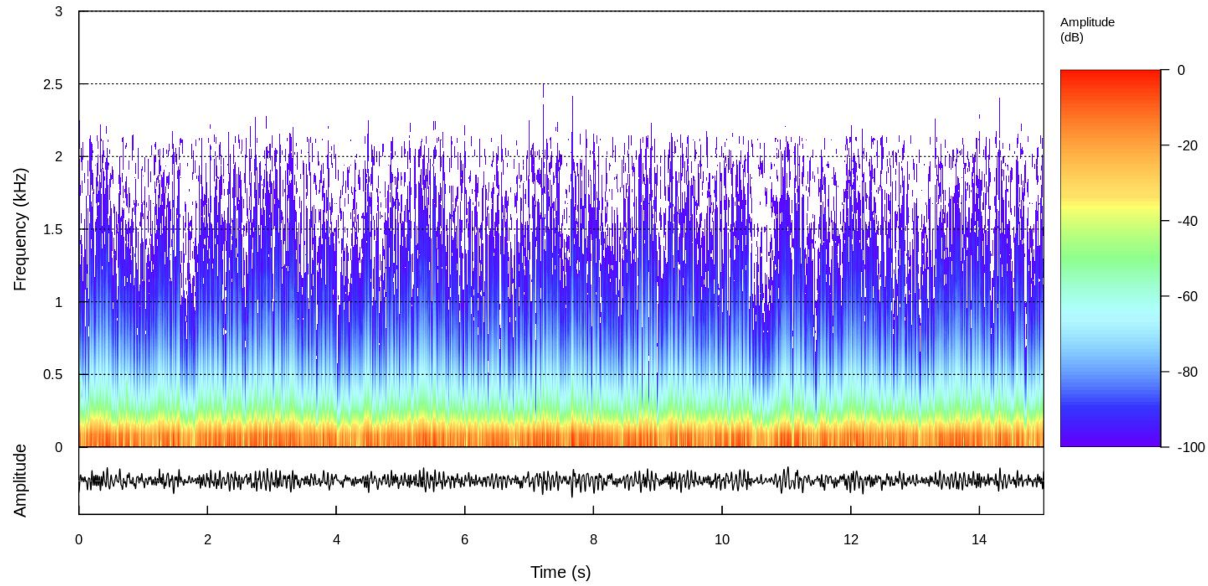

Fig 6: Spectrogram of whale and ship

Waveforms

An overlay of the waveforms is perhaps a better revealer of the disturbance than the spectrogram (fig. 7).

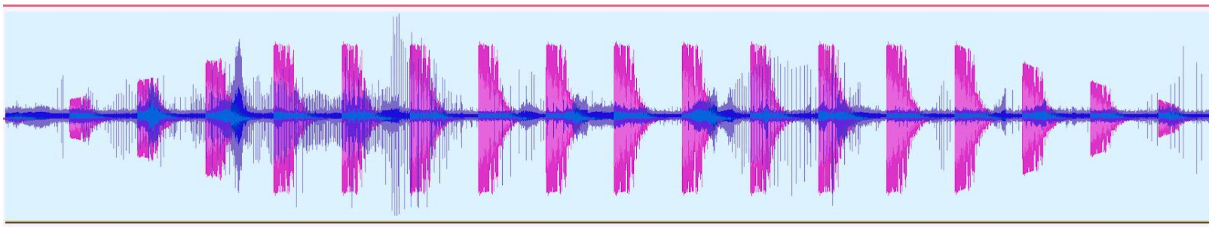

Fig. 7: Overlay of waveforms of orca and sonar.

Waveforms can also be combined algorithmically using logical functions. An XOR overlay of the waveforms of the ship (in red) and the whale (in white) is perhaps a useful visualization. As the overlap is rendered in a different color (light blue), this illustrates that the sound channel used by the whale is saturated by the ship (fig. 8).

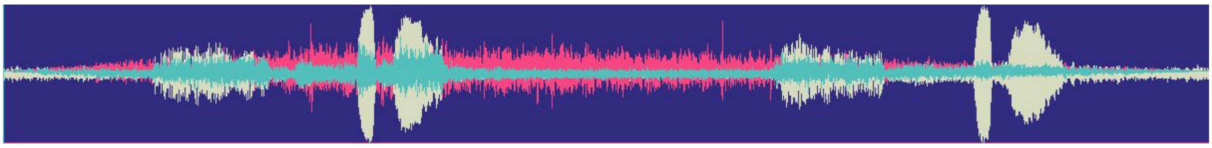

Fig. 8: Overlay of waveforms of whale and ship.

Other visualizations

Ferguson, Moere, Cabrera [2005] have shown that mapping noisiness to random movement is intuitively understandable without previous training. Modulating the readability of the text accompanying the sounds, using the rhythmical patterns of the noise, would be in my opinion a very effective way of making a lasting impression and conveying the message (fig. 9, 10).

> Vor allem die großen Meeressäugetiere profitieren von den so möglichen großen Kommunikationsreichweiten und haben verschiedene Möglichkeiten entwickelt, um die gute Schallübertragung des Meeres zu nutzen. Der Blauwal – das größte Lebewesen der Erde – erzeugt tieffrequente Töne, die ganze Ozeanbecken durchdringen können. Trotz der Lautstärke reicht seine Signalstärke allein hierfür nicht aus, sondern er nutzt gezielt besonders gut schallleitende Wasserschichten, wie z.B. den in größeren Tiefen auftretenden SOFAR-Kanal. Die dortigen Bedingungen schaffen ideale Voraussetzungen für die globale Kommunikation von Walen.

Fig. 9: shaking the text using the rhythmical patterns of the ship

Fig. 10: Fading the text using the rhythmical patterns of the sonar

Literature review

In an attempt to find answers to the questions below, literature on the following fields was reviewed:

- Marine bioacoustics literature [Au & Hastings, 2008, Erbe et al., 2016]
- Visualizations for speech pedagogy and the hearing-impaired [Walker, 1987]
- Visualizations for music training [Ferguson et al, 2005]

What characteristics of underwater sound transmission differ significantly from airborne sound transmission, and would therefore need to be emphasized?

The main effect of concern here is that sound can propagate further in the ocean than in the atmosphere, due to the reverberation of sound caused by layers of different temperature and salinity within the water column [Au & Hastings, 2008].

Sound propagation in seawater, specifically its masking potential, is affected mainly by three distance-related effects (Erbe et al., 2015):

- The spectrum of sound is dampened as a function of distance, as higher frequencies are absorbed more rapidly than lower frequencies.
- Sound reflections at the water surface and at the sea bottom result in interference phenomena which can change the frequency spectrum of the perceived noise. This phenomenon (Lloyd Mirror effect) is particularly present at short distances (e.g. passing ships).
- Frequency dispersion affects the spectral and temporal structure of perceived sounds, resulting in stretched sounds at several km distance.

What characteristics of sound perception by marine mammals underwater differ significantly from airborne sound perception, and would therefore need to be translated for human senses?

As can be seen in the Animal Audiogram Database, marine mammals have very diverse hearing thresholds and range underwater. These ranges lie outside of the human hearing range in most cases.

Which acoustic parameters are necessary and sufficient for characterizing underwater sounds?

The more complex the sound, the more "diffuse and arbitrary" the mapping between auditory and visual representation [Walker, 1987]. A digital audio file can be analysed using Fourier transform algorithms to extract relevant parameters [Ferguson, Moere, Cabrera, 2005]: harmonics within the sound, noisiness, pitch and loudness. A simpler approach is favored by Walker [1987]: frequency, waveform, amplitude and duration.

How can these parameters be mapped to visual elements, which metaphors are applicable?

Walker [1987] remarks that certain stimuli are amodal, i.e. the concepts of intensity, amplitude and duration can be understood both acoustically or visually, e.g. sound intensity can be translated into light intensity. These stimuli are particularly interesting for cross-modal transfer of information. By contrast, certain stimuli appear to be modal, e.g. pitch. In Ferguson, Moere, Cabrera [2005], harmonics are mapped to spacing, noisiness to random movement, pitch to balance, loudness to size. In Walker [1987], frequency is matched to vertical placement, waveform to shape, duration with horizontal length, amplitude with size. Walker [1987] remarks that the correspondence from frequency to vertical placement is more consistent in subjects with musical training.

What are the applicable quality control indicators (qualitative and quantitative) that can ensure that the visualization is fit for purpose?

Suggestions on various possible quality tests can be extracted from literature:

- Asking test subjects to describe visual elements in the visualisation in acoustic terms. See Walker [1987] for inspiration.
- Asking test subjects to differentiate between selected "good" and "bad" sound situations, while experimenting with the visualization [Ferguson, Moere, Cabrera, 2005].
- Providing a standard as a baseline for categorizing or comparing specific sound parameters is a typical setup in auditory perception experiments [Walker, 1987]. Test users could be asked to compare a test soundscape with the standard and to judge whether the situation in the soundscape has "more" or "less" of a specific parameter (e.g. is noisier).

Note: Musical training has a significant impact on the choice of visual metaphors for sounds; age is less important than musical training; the impact of culture is indecisive [Walker, 1987].

Links

Sounds

- Acoustic communication in fishes: https://homepage.univie.ac.at/friedrich.ladich/
- Fish sounds: http://www.gso.uri.edu/fishsounds/CDindex.html
- Links for passive acoustic and fish sound web pages: http://www.fishecology.org/soniferous/Passive%20acoustic%20links.htm

- Sound in the sea, Fishes: https://dosits.org/galleries/audio-gallery/fishes/

MfN projects

- Inside Tumucumaque: https://www.inside-tumucumaque.com/
- Mediasphere Audio example: http://mfn0006.naturkundemuseum-berlin.de:3200/detail/34549952

External projects

- Das Toximeter Projekt (aus Schweden): https://toximeter.nrm.se/ https://doi.org/10.1016/j.envpol.2012.07.017
- Gapminder https://www.gapminder.org/
- Clear Seas https://clearseas.org/en/underwater-noise/

Visualization libraries

- https://wavesurfer-js.org/
- https://d3js.org/ Beispiele unter: https://github.com/d3/d3/wiki/Gallery

Sources

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Appendix A

Underwater hearing ranges for various marine animals (in kHz).

Animal	Taxon	Hearingmin (kHz)	Hearing max (kHz)	Source hearing
North Atlantic right whale	Baleen whales	0.01	22	Parks et al., 2007
Sperm whale	Toothed whales	0.1	60	Ridgway and Carter, 2001; Siebert et al., 2018
Beluga whale	Toothed whales	1.3	150	Sysueva, 2018; Mooney et al, 2018; Garland et al., 2015

Killer whale	Toothed whales	0.6	114	Branstetter et al., 2017
Pilot whale	Toothed whales	0.32	64	Pacini et al., 2010; Siebert et al., 2018; Randall et al., 1999 in Morisaka & Connor, 2007
Bottlenose dolphin	Toothed whales	0.94	180	Finneran et al., 2008; Diaz Lopez, Bernal Shirai, 2009; Wang et al., 1995 cited in Morisaka & Connor, 2007
Risso's dolphin	Toothed whales	1.9	110	Nachtigall et al., 2005;Corkeron & van Parijs, 2001; Rendell et al., 1999 in Morisaka & Connor, 2007
Striped dolphin	Toothed whales	0.5	160	Kastelein et al., 2003
Harbour porpoise	Toothed whales	2.5	180	Kastelein et al., 2002
Harbour seal	Seals	0.025	40	Wolski et al., 2003; Reichmuth et al., 2013; Hanggi & Schustermann, 1994
West Indian manatee	Sea cows	0.95	90.5	Gaspard et al., 2012
Cod	Bony fishes	0.03	0.47	Chapman & Hawkins, 1973
Loggerhead sea turtle	Turtles	0.05	1.1	Lavender et al., 2014
Grey seal	Seals	0.1	15	Ridgway & Joyce, 1975 cited in Erbe et al., 2016;Asselin et al., 1993
Harp seal	Seals	0.7	100	Terhune & Ronald, 1972 cited in Erbe et al., 2016; Moors & Terhune, 2003

Underwater vocalization ranges of selected marine animals

Animal	Taxon	Voc min	Voc max	Source voc	Clicks min	Clicks max	Source clicks

		(kHz)	(kHz)		(kHz)	(kHz)	
North Atlantic right whale	Baleen whales	0.3	0.6	Vabderlaan et al., 2003	NA	NA	NA
Sperm whale	Toothed whales	0.1	30	Siebert et al., 2018	5	24	Madsen et al., 2002 in Morisaka & Connor, 2007
Beluga whale	Toothed whales	1.3	5.7	Garland et al., 2015	46.6	125.7	Nakamura 1999 in Morisaka & Connor, 2007
Killer whale	Toothed whales	1.5	18	Siebert et al., 2018	45	80	Au et al., 2004 in Morisaka & Connor, 2007
Pilot whale	Toothed whales	0.32	21.2	Siebert et al., 2018; Randall et al., 1999 in Morisaka & Connor, 2007	NA	NA	NA
Bottlenose dolphin	Toothed whales	0.94	23	Diaz Lopez, Bernal Shirai, 2009; Wang et al., 1995 cited in Morisaka & Connor, 2007	34.5	131.9	Nakamura, 1999 in Morisaka & Connor, 2007
Risso's dolphin	Toothed whales	1.9	23.8	Corkeron & van Parijs, 2001; Rendell et al., 1999 in	30	100	Philips et al., 2003 in Morisaka & Connor, 2007

				Morisaka & Connor, 2007			
Striped dolphin	Toothed whales	8.1	14.8	Oswald et al., 2003 in Morisaka & Connor, 2007	0.3	100	Kastelein et al., 2003
Harbour porpoise	Toothed whales	NA	NA	NA	118.9	128.4	Au et al., 1999 in Morisaka & Connor, 2007
Harbour seal	Seals	0.025	4	Hanggi & Schusterman, 1994	NA	NA	NA
West Indian manatee	Sea cows	2.5	7	Nowacek et al., 2003	NA	NA	NA
Cod	Bony fishes	0.05	0.5	Caiger et al., 2020	NA	NA	NA
Loggerhead sea turtle	Turtles	NA	NA	NA	NA	NA	NA
Grey seal	Seals	0.1	3	Asselin et al., 1993	NA	NA	NA
Harp seal	Seals	0.7	6	Moors & Terhune, 2003	NA	NA	NA