SONIFICATION OF PHYSICAL QUANTITIES THROUGHOUT HISTORY: A META-STUDY OF PREVIOUS MAPPING STRATEGIES

Gaël Dubus and Roberto Bresin

KTH Royal Institute of Technology
Department of Speech, Music and Hearing
Stockholm, Sweden
{dubus,roberto}@kth.se

ABSTRACT

We introduce a meta-study of previous sonification designs taking physical quantities as input data. The aim is to build a solid foundation for future sonification works so that auditory display researchers would be able to take benefit from former studies, avoiding to start from scratch when beginning new sonification projects. This work is at an early stage and the objective of this paper is rather to introduce the methodology than to come to definitive conclusions. After a historical introduction, we explain how to collect a large amount of articles and extract useful information about mapping strategies. Then, we present the physical quantities grouped according to conceptual dimensions, as well as the sound parameters used in sonification designs and we summarize the current state of the study by listing the couplings extracted from the article database. A total of 54 articles have been examined for the present article. Finally, a preliminary analysis of the results is performed.

1. INTRODUCTION

History is rich with examples of uses of the auditory modality to represent phenomena from the physical world. The use of auditing in Mesopotamia as early as 3500 BCE to detect anomalies in accounts of commodities could be regarded as one of the first implementations of data sonification [1]. Auditory displays have been exploited to perceive various physical dimensions such as temporal, physiological or kinematic variables long before concepts such as audification and sonification were formalized: automatic alarm signals and striking clocks were already used in ancient Greece (for example by combining a clepsydra with a water organ [2]) and medieval China to provide information about elapsed time. The stethoscope, which can be considered as performing the audification of heart rate, breath and blood pressure among others, was invented by Laënnec in 1816. Pythagoreans reportedly defined a musical scale by associating different tones to heavenly bodies according to their apparent velocity as seen from the Earth. Inspired by this approach in his treatise *Harmonices Mundi* (1619), Kepler transposed the Pythagorean concept of ἁρμονία τῶν σφαιρῶν (harmony of the spheres) onto an heliocentric system: he assigned each planet a fundamental tone depending on its maximum distance to the sun – the aphelion – which was then changed in pitch depending on the angular displacement of the planet as seen from the sun, thus covering a specific interval as the planet moved around its orbit. This led him to focus on an harmonic relationship between the mean distance and the orbital period of a celestial body, which he finally discovered and exposed in his Third Law of Planetary motion [3].

More recent applications of auditory displays were sparsely introduced during the twentieth century (Pollack and Ficks [4] in 1954, Speeth [5] in 1961, Kay [6] in 1974) but the starting point of the outburst of research in this field was probably the first ICAD conference in 1992 and the subsequent seminal work edited by Kramer [7]. Sonification, a particular case of auditory display aiming at underlining relationships within the data, is therefore a relatively recent matter of concern for scientists, yet it has now begun to gain some maturity in nearly twenty years of research. Even if sonification is a narrow niche of interdisciplinary applied sciences – as compared to scientific visualization for example – the community of researchers has grown significantly to now produce burgeoning examples of practical applications. There exist however an obvious need for homogenizing the findings in the field, and attempts to tackle this lack of unity are still being made by putting forward design guidelines and by introducing sound theoretical frameworks (see [8, 9, 10, 11] for a couple of examples in the past few years). In his doctoral dissertation, Worrall [1] summarizes former attempts, then provides a comprehensive classification of the different types of data sonification.

Probably one of the most well-known devices to integrate an auditory display system – popular among the public and emblematic for sonification researchers – is the Geiger counter, which translates ionizing radiation into clicks with a pulse depending on the level of radiation. But what made it so popular? Originally, this particular auditory feedback was designed as a complement to visualization performed on the earliest devices by an electrometer, since this tedious method of measurement was not entirely satisfying. A sensitive telephone was first incorporated in the electrical circuit in order to listen to the audification of electrical impulses due to the ionization of the gas in the tube of the counter [12]. This was not the first time that this setup, which could in fact be considered a descendant of telegraph sounder, was used (see a similar example of audification of magnetically induced current [13]) and it later evolved to include more advanced components for amplification and recording, loudspeakers or headphones. Taking a step backwards to consider this system not as audification of electrical current but, as we introduced it, as sonification of the level ionizing radiation, one could bring up the question of the mapping strategy. Therein may lie the actual key of its success: transposing a physical quantity which is essentially non-visual and pictured in everyone's imagination as very important because life-threatening, to the auditory modality through clicks with a varying pulse.

The aim of our study is to look at previous sonification designs in order to perform a meta-analysis of the mappings involving physical quantities present in the literature. By these means, we could investigate whether some particular associations between physical quantities and sound parameters can be considered as inherently more informative than others. Previous work on sonification mappings has been initiated by Walker [14], who split up the design process of parameter mapping sonification into three subphases: choice of the mapping strategy – *i.e.* which sound parameter to use to represent a specific data dimension, choice of polarity and psychophysical scaling. His work, based on perceptual studies to conduct the entire design process following these three successive stages, only dealt with a limited number of generic data dimensions (*e.g.* "Temperature", "Pressure", "Velocity"...). The present project rather aims at collecting an extended set of variables associated to physical quantities in order to focus on the mapping strategies used in previous works. Following the methodology presented in section 2, a statistical analysis will be performed over a large collection of sonification projects in order to extract information such as the sound parameters which are used the most in the design of sonification systems, the most popular one-to-one couplings and some trends in associations of higher-level categories of data to sound parameters.

This work is at an early stage and the purpose of this paper is mainly to explain our method. Since the number of projects considered in this article is still very low for the purposes of a meta-study, only a simple analysis is presented in section 5, more advanced statistics being planned for future developments.

2. METHODOLOGY

The method for the present work was inspired by Juslin and Laukka's meta-analysis of the communication of emotions in vocal expression and music performance [15]. In their study, they reviewed 104 studies of vocal expression and 41 studies of music performance. We therefore started our study by collecting a large pool of scientific publications. We looked for papers that could be potentially valuable for our study by browsing a set of scientific digital libraries (IEEE Xplore, ScienceDirect, SpringerLink, Ingentaconnect, ASA Digital Library, PubMed) and proceedings of specialized conferences (ICAD, ISon, CHI).

The first step of the selection was a filtering by the only keyword *sonification*, which typically gave a few hundreds of results. The articles dealing with the chemical definition of sonification – sonic stimulation or irradiation by sound or ultrasound waves – were immediately discarded. We were aware that this process alone would not allow to include projects earlier than the formalization of auditory display techniques in the beginning of the 1990s. As a first criterion of inclusion in our database, the title or the abstract of the article had to foreshadow the implementation of a practical application: it should not be too general like the presentation of a new software platform for sonification, nor too theoretical like the introduction of a taxonomy or a design framework. Sonification of abstract data such as stock market data or web server logs was left aside as we focused only on physical quantities. Additional articles were then integrated in our database when interesting references were found while reading articles from the initial pool. In this way, significant works which nowadays could be considered as sonification but were published before the 1990s could also be included subsequently.

The second step was to aggregate articles corresponding to the same *project*, the publication of which had been spread over a couple of years. Such articles were either collected in the first place by browsing the scientific databases and flagged as similar work – generally having several common authors and close dates of publication – or referred to in the more recent papers of the project. In this fashion, we are able to track the evolution of the work and spot the successful mapping strategies (assessed as such by the authors or emerging from perceptual experiments).

The question of the type of information to extract is of primary importance in such a study. What we want to do is primarily a census report of mapping strategies. Therefore, we are only interested in conscious choices of the designer: artifacts of the sonification system leading to *a posteriori* associations perceived by listeners were not considered in this study. As an example inspired by a Model-Based Sonification implemented by Sturm [16], one can consider a set of particles moving in a space subject to given physical laws of motion, each particle producing a pure tone of frequency depending on its velocity. An increase of temperature of the system would give rise to a higher perceived pitch of the sound feedback due to an increased overall velocity, but since the sonification design is not specifically mentioning the coupling *temperature vs. pitch*, the only association to be retained is *velocity vs. frequency*. Moreover, in the case of multimodal feedback, associations of physical quantities relative to the interaction design (such as the force of a haptic feedback) but external to the data sonification in itself are not taken into account either.

Since we are unable at this stage to foresee the extent to which the authors will evaluate their own strategies, we decided to assign different labels to the found couplings according to the following classification:

- not implemented but mentioned as future work
- implemented but not assessed
- assessed as good
- assessed as poor

Even limiting ourselves to physical quantities, we can expect a great diversity of sonified variables to come up from the collected projects, given that sonification can be applied in many different contexts. For this reason, although it may be interesting to look at the mappings of these variables separately, advanced analysis requires to group them into specific categories. As an example, data corresponding to temperature when sonifying daily weather records should be placed in the same category as the sonified core temperature of a nuclear reactor. This approach can be seen as the inverse process of the experimental protocol of Walker [14], the subjects being asked to think about variations in "Temperature" without any more precision while listening to experimental sound samples. This grouping into generic conceptual dimensions is rather straightforward in this particular example, yet it might not always be the case. A preliminary classification based on the sole intuition of the authors of the present article – at the risk of being highly subjective – is presented in section 4. Future work will include a more rigorous classification based on the opinion of other researchers.

We expect the authors of the collected articles to make use of different levels of description: one could describe a mapping as changing the *timbre* depending on the *spatial location* of the sonified data, while another may detail precisely which modifications are realized on the sound spectrum of the auditory feedback. Therefore, in addition to the sonified data variables, the sound attributes used as output parameters of the sonification design are also grouped together into categories for the purposes of the analysis as presented below.

The statistical analysis itself is limited at this stage and only consists in an inventory of the most commonly used couplings, as well as of the most popular sound parameters used in the sonification design. We expect the sound attributes known as most salient (such as *pitch*) to be used more often. Finally, we make an attempt to spot trends of associations between higher-level categories of data variables and higher-level categories of sound parameters.

3. COLLECTED PAPERS

As for now, 299 papers have been included in our database following the process presented in section 2: 225 were part of the original pool and 74 have been added from references. A total of 64 papers have been studied so far, 10 of which has been judged as not including enough information to be taken into account in the present work – mainly because the same information was already present in other publications of the same project. Table 2 summarizes the mapping strategies identified in 54 papers corresponding to 21 different projects. Due to the small number of couplings with the label *assessed as poor*, these were ignored in this preliminary analysis and are not presented in Table 2. Since there is also much to be learnt from these unsuccessful strategies, they will definitely be included in future extensions of the present work. The other couplings were not distinguished, the great majority of them being flagged as *implemented but not assessed*.

4. LIST OF VARIABLES AND CLASSIFICATION

In this section, we provide a comprehensive list of the sound parameters used in the works included in our database (see Table 2), as well as a comprehensive list of the physical quantities corresponding to the sonified data. Unlike the sound parameters, the various physical quantities are not transcribed directly from the articles: we made a first attempt to merge different variables into more general dimensions. For example, the data referring to the category *reflectiveness* includes both light reflectiveness and the reflection coefficient of a wall, an architectural acoustic quantity. In both cases though, we tried to group the variables according to their nature, as explained in section 2. We are aware that this grouping is debatable and this preliminary version will be updated as we add more articles to our database. By assigning a letter to the sound parameters and a number to the physical quantities, we are then able to refer to specific couplings in the summarizing table: as an example, the code M4 will be referring to a coupling *tempo vs. Velocity*.

4.1. Sound parameters

4.1.1. Pitch-related aspects

A. pitch, frequency, fundamental frequency
B. melody
C. harmony, consonance or dissonance
D. pitch range, frequency band

4.1.2. Timbral aspects

E. timbre, texture
F. instrumentation, accompaniment
G. voice gender
H. duration: spectral time scale (< 50 ms), grain duration
I. spectral envelope, spectral energy distribution, formants
J. roughness
K. brightness, spectral centroid, modulation index, richness, sharpness
L. speech model: vowel

4.1.3. Temporal aspects

M. tempo
N. duration: rhythmic time scale (> 100 ms, < 2 s), rhythmic stability, metric regularity, fluctuation strength
O. duration: event time scale (> 2 s), frequency of events
P. duration: ambient time scale
Q. time ordering, sequential position

4.1.4. Loudness-related aspects

R. sound intensity, sound level, volume, loudness, amplitude, amplitude envelope, grain sound level
S. dynamic intensity, dynamic loudness

4.1.5. Spatialization

T. stereo channel, spatialization, stereo panning, interaural time difference, interaural intensity difference
U. movement of the sound source, Doppler effect

4.1.6. Onsets

V. onset time, attack time, onset sharpness

4.1.7. Saliency

W. speech model: voiced/unvoiced ratio

4.2. Sonified physical quantities

4.2.1. Kinematics: position, motion

1. Location
2. Orientation
3. Distance
4. Velocity
5. Acceleration
6. Jerkiness
7. Motion
8. Frequency of motion

4.2.2. Matter

9. Material
10. Density
11. Radioactivity
12. Porosity
13. Electrical conductivity
14. Reflectiveness
15. Transmission coefficient

4.2.3. Kinetics: force, energy, activity, intensity

16. Overall activity
17. Temperature
18. Pressure
19. Intensity
20. Force
21. Overall potential

4.2.4. Proportions

22. Size
23. Shape
24. Mass
25. Room reverberation time
26. Room modal distribution

4.2.5. Time-Frequency

27. Wavelength, Frequency
28. Spectrum
29. Spectral power
30. Spectral distribution
31. Synchronization
32. ITA index of EEG (theta to alpha ratio)
33. Acoustical modulation transfer function, Room impulse response
34. Roughness (sound)
35. Fluctuation strength (sound)
36. Raw time series

5. PRELIMINARY ANALYSIS

Since this work is at an early stage, we did not collect enough data to perform an advanced statistical analysis. Therefore, only simple informations will be extracted at this point. The most straightforward quantity to derive is the number of projects using a given coupling, obtained by simply summing over the summarizing table. This operation gives the following ranking of couplings:

1. T1 (*spatialization vs. Location*): 9 occurrences
2. A1 (*pitch vs. Location*): 8 occurrences
3. R3 (*sound level vs. Distance*): 5 occurrences
4. A3 (*pitch vs. Distance*), A10 (*pitch vs. Density*), A27 (*pitch vs. Wavelength-Frequency*), F27 (*instrumentation vs. Wavelength-Frequency*): 4 occurrences
5. A4 (*pitch vs. Velocity*), A22 (*pitch vs. Size*), E1 (*timbre vs. Location*), E27 (*timbre vs. Wavelength-Frequency*), M4 (*tempo vs. Velocity*): 3 occurrences

Considering only this first result, one can already make a couple of observations. First, many of these couplings seem to follow the logic of ecological perception: location is usually determined by the human auditory system thanks to the Interaural Time Difference, which can be related to spatialization of the sound in a sonification design. In a same manner, distance is ecologically related to sound level, frequency and size to pitch, velocity to tempo. Second, among the 23 sound parameters listed in section 3, only a few are present within the most popular couplings, and pitch is apparently overrepresented. It might then be interesting to look at the frequency of use of the sound parameters in sonification designs. Computing the percentage of projects using given sound parameters, we obtain the following leading variables:

	Kinem.	Matter	Kinet.	Prop.	T.-Freq.
Pitch-rel.	21	9	7	9	10
Timbral	20	14	6	11	22
Temporal	18	13	3	4	6
Loudness-rel.	9	5	9	2	2
Spatialization	16	-	-	1	2
Onsets	-	-	-	1	-
Saliency	1	-	-	-	-

Table 1: Couplings sorted according to high-level categories

1. *pitch*: 86%
2. *sound level*: 62%
3. *spatialization*: 57%
4. *timbre* and *rhythmic time scale*: 43%

This denotes clearly a prominence of the use of pitch in sonification mapping strategies. However, a more balanced result is obtained when performing the same computation for higher-level categories of sound parameters. Many projects are indeed using variables from several subcategories at the same time. Table 1 shows the number of collected couplings grouped by the categories introduced in section 3. Due to the limited number of projects, it is difficult to draw some definitive conclusions at this stage. Nevertheless, an interesting observation is that spatialization is almost only used to render kinematic quantities. This table also shows that the most often used quantities for input of a sonification system are kinematic quantities, but this might be due to the present selection of projects and therefore not being representative of the complete database.

6. CONCLUSION

We presented an early version of a meta-study of sonification works taking physical quantities as input data. We could already make a couple of assumptions which would be interesting to reconsider at a later stage. These preliminary results include the apparent imitation of ecological perception of sounds among the most popular couplings as well as the prominence of pitch, known to be one of the most salient attributes of sound. The statistical analysis was limited by the relatively small number of projects studied in the present article, and we hope to be able to bring to light additional trends in the design of sonification. In this way, this work could serve as a basis for future sonification designs.

7. ACKNOWLEDGMENT

This work was supported by the Swedish Research Council, Grant Nr. 2010-4654.

Project ID	References	Summary of the work from a sonification perspective	Sound material	Mapping references
01	[17, 18, 19]	Sonification of aquarium fishes and ants behavior	Use of the MIDI protocol to control digital synthesizers and samplers, piece of music	A1, A22, A27, B10, B22, B23, E1, E2, E14, E22, E23, E27, F10, F14, F16, F22, F23, F27, G22, G23, G27, M4, M5, M16, N4, R1, R3, R10, R16, T1, T2
02	[20]	Design recommendations for the sonification of large spatial datasets	Environmental sounds	H3, H7, N1, N3, N7, N16, O1, T1
03	[21]	Sonification of acoustic properties and audio data	Various stimuli including noise bands, pure tones and complex tones	A19, A26, A27, A30, A33, C26, D30, H33, I33, J34, K30, N14, N25, N35, O33, R14, R15, R19, T31, T33
04	[22, 23, 24, 25, 26]	Real-time sonification of colored images and videos	Instrument sounds	A19, A29, E27, F27, F29, N3, R3, T1
05	[27, 28, 29]	Sonification of video clips of counter movement jumps	Synthesized voice and tone modulated in amplitude and frequency	A20, R20
06	[30, 31, 32, 33]	Sonification of human EEG: in real-time as a help for positioning surging instruments; as a tool for *a posteriori* analysis of long recordings	Samples and environmental sounds modulated in pitch, volume and balance	A1, A32, H7, H23, O7, T1, T7
07	[34]	Art installation: an immersive virtual world making use of sonification	Filtered noise bursts, wide band signal, substractive synthesis instruments	A1, A10, I10, N10, P10, T1
08	[35]	Sonification of contour maps (spatial data)	Piano tone samples	A3, D22, R3, T1, T3, U7, U23
09	[36, 37, 38, 39]	Sonification of the motion of a rowing boat	Pure tone with gliding frequency, xylophone from a MIDI synthesizer, piece of music with variable tempo, vocal formant synthesis	A5, K6, M8, R5
10	[40]	Sonification of meteorological data (hail storms)	FM instruments, FM synthesis	A1, E1, O22, R1, R22, T1
11	[41, 42]	Sonification of geophysical maps	MIDI synthesizer	A2, A10, A17, E2, E10, F2, F10, M2, M10, N2, N10
12	[43, 44]	Sonification of well-logs	Granular synthesis, timbre grains for musical instruments	A10, A11, A12, A13, E9, H10, H11, H12, H13, O10, O11, O12, O13, O36, T2
13	[45, 46, 47, 48]	Sonification of: activity in social spaces, motion of a calf, movements of a violin player, free gestures	Particular focus on esthetics, use of Max/MSP/Jitter and MIDI commands	A1, A2, A3, A4, A5, A7, A22, C16, E1, E5, E10, E16, M4, O7, O10, R5, R16, S10, S16, S19, T7
14	[49, 50, 51, 52]	Sonification of textured MRI images	Synthesized speech-like sounds	A27, E27, H27, I22, I23, I27, I28, N22, N27, Q2
15	[53, 54, 55, 56, 57, 58]	Psychoacoustical study of sonification mapping strategies	Pure tones, FM synthesis	A3, A4, A10, A17, A18, A22, A24, K3, K4, K17, K18, K22, K24, M3, M4, M10, M17, M24, R10, R17, R18, R22, V22
16	[59]	Sonification of position accuracy of address location	Piano tones	A1
17	[60]	Navigation in a virtual space including auditory targets	Songs	R3, U7
18	[61]	Sonification of running mechanics	Samples of environmental sounds	I7
19	[62, 63, 64]	Spectral Mapping Sonification of human EEG	Pure tones, coupled oscillators	A1, A3, A27, A29, D1, E31, F1, F27, H29, I29, J31, K1, N29, Q1, R29, R31, T1
20	[65, 66, 67, 68]	Event-Based Sonification of human EEG	Blip oscillator with vibrato, harmonic tones modulated with a percussive envelope, synthesis from pink noise grains	A1, E7, F27, K27, K31, N27, R19, T1
21	[69, 70]	Kernel Regression Mapping Sonification of human EEG	Substractive synthesizer for simple speech-like sounds	A4, I1, I3, I7, I21, L21, R3, W3

Table 2: Summary of the meta-analysis at the current stage

8. REFERENCES

[1] D. Worrall, "Chapter 2: An overview of sonification," in: *Sonification and information: Concepts, instruments and techniques*, Ph.D. dissertation, University of Canberra, Canberra, Australia, March 2009.

[2] J. W. Humphrey, J. P. Oleson, and A. N. Sherwood, *Greek and Roman technology: a sourcebook.* Routledge, 1998.

[3] B. R. Gaizauskas, "The harmony of the spheres," *Journal of the Royal Astronomical Society of Canada*, vol. 68, no. 3, pp. 146–151, 1974.

[4] I. Pollack and L. Ficks, "Information of elementary multidimensional auditory display," *J. Acous. Soc. Amer.*, vol. 26, pp. 155–158, 1954.

[5] S. D. Speeth, "Seismometer sounds," *J. Acous. Soc. Amer.*, vol. 33, no. 7, pp. 909–916, 1961.

[6] L. Kay, "A sonar aid to enhance spatial perception of the blind: engineering design and evaluation," *The Radio and Electronic Engineer*, vol. 44, no. 11, pp. 605–627, 1974.

[7] G. Kramer, Ed., *Auditory display: sonification, audification and auditory interfaces.* Addison Wesley Publishing Company, 1994.

[8] A. de Campo, "Toward a data sonification design space map," in *Proceedings of the 13th International Conference on Auditory Display (ICAD2007)*, Montreal, Canada, 2007.

[9] T. Hermann, "Taxonomy and definitions for sonification and auditory display," in *Proceedings of the 14th International Conference on Auditory Display (ICAD2008)*, Paris, France, 2008.

[10] S. Barrass, "Stream-based sonification diagrams," in *Proceedings of the 14th International Conference on Auditory Display (ICAD2008)*, Paris, France, 2008.

[11] C. Frauenberger and T. Stockman, "Auditory display design – An investigation of a design pattern approach," *International Journal of Human-Computer Studies*, vol. 67, no. 11, pp. 907–922, 2009.

[12] A. F. Kovaric, "New methods for counting the alpha and the beta particles," *Physical Review*, vol. 9, no. 6, pp. 567–568, Proceedings of the American Physical Society: Minutes of the Stanford meeting, 1917.

[13] D. E. Hughes, "Molecular magnetism," *Proceedings of the Royal Society of London*, vol. 32, pp. 213–225, 1881.

[14] B. N. Walker, "Magnitude estimation of conceptual data dimensions for use in sonifications," Ph.D. dissertation, Rice University, Houston, TX, USA, September 2000.

[15] P. N. Juslin and P. Laukka, "Communication of emotions in vocal expression and music performance: different channels, same code?" *Psychological Bulletin*, vol. 129, no. 5, pp. 770–814, 2003.

[16] B. L. Sturm, "Sonification of particle systems via de Broglie's hypothesis," in *Proceedings of the 6th International Conference on Auditory Display (ICAD2000)*, Atlanta, GA, USA, 2000.

9. REFERENCES USED IN THE META-STUDY

[17] B. N. Walker, M. T. Godfrey, J. E. Orlosky, C. Bruce, and J. Sanford, "Aquarium sonification: soundscapes for accessible dynamic informal learning environments," in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*, London, UK, 2006.

[18] B. N. Walker, J. Kim, and A. Pendse, "Musical soundscapes for an accessible aquarium: bringing dynamic exhibits to the visually impaired," in *Proceedings of the International Computer Music Conference (ICMC 2007)*, Copenhagen, Denmark, 2007.

[19] A. Pendse, M. Pate, and B. N. Walker, "The accessible aquarium: identifying and evaluating salient creature features for sonification," in *Assets '08: Proceedings of the 10th international ACM SIGACCESS conference on Computers and accessibility*, Halifax, Canada, 2008.

[20] S. Saue, "A model for interaction in exploratory sonification displays," in *Proceedings of the 6th International Conference on Auditory Display (ICAD2000)*, Atlanta, GA, USA, 2000.

[21] D. Cabrera, S. Ferguson, and R. Maria, "Using sonification for teaching acoustics and audio," in *Proceedings of ACOUSTICS 2006*, Christchurch, New Zealand, 2006.

[22] G. Bologna, B. Deville, and T. Pun, "Pairing colored socks and following a red serpentine with sounds of musical instruments," in *Proceedings of the 14th International Conference on Auditory Display (ICAD2008)*, Paris, France, 2008.

[23] ——, "On the use of the auditory pathway to represent image scenes in real-time," *Neurocomputing*, vol. 72, no. 4–6, pp. 839–849, 2009.

[24] B. Deville, G. Bologna, M. Vinckenbosch, and T. Pun, "See ColOr: seeing colours with an orchestra," in *Human Machine Interaction.* Springer Berlin / Heidelberg, 2009, pp. 251–279.

[25] G. Bologna, B. Deville, and T. Pun, "Blind navigation along a sinuous path by means of the See ColOr interface," in *Bioinspired Applications in Artificial and Natural Computation.* Springer Berlin / Heidelberg, 2009, vol. 5602, pp. 235–243.

[26] ——, "Sonification of color and depth in a mobility aid for blind people," in *Proceedings of the 16th International Conference on Auditory Display (ICAD2010)*, Washington, DC, USA, 2010.

[27] A. O. Effenberg, "Movement sonification: effects on perception and action," *IEEE Multimedia*, vol. 12, pp. 53–59, 2005.

[28] ——, "Movement sonification: motion perception, behavioral effects and functional data," in *Proceedings of the 2nd International Workshop on Interactive Sonification (ISon 2007)*, York, UK, 2007.

[29] L. Scheef, H. Boecker, M. Daamen, U. Fehse, M. W. Landsberg, D.-O. Granath, H. Mechling, and A. O. Effenberg, "Multimodal motion processing in area V5/MT: evidence from an artificial class of audio-visual events," *Brain Research*, vol. 1252, pp. 94–104, 2009.

[30] E. Jovanov, D. Starčević, V. Radivojević, A. Samardžić, and V. Simeunović, "Perceptualization of biomedical data. An experimental environment for visualization and sonification

of brain electrical activity," *IEEE Engineering in Medicine and Biology Magazine*, vol. 18, no. 1, pp. 50–55, 1999.

[31] E. Jovanov, K. Wegner, V. Radivojević, D. Starčević, M. S. Quinn, and D. B. Karron, "Tactical audio and acoustic rendering in biomedical applications," *IEEE Transactions on Information Technology in Biomedicine*, vol. 3, pp. 109–118, 1999.

[32] E. Jovanov, D. Starčević, A. Marsh, Ž. Obrenović, V. Radivojević, and A. S. c, "Multi modal presentation in virtual telemedical environments," in *High-Performance Computing and Networking*. Springer Berlin / Heidelberg, 1999, vol. 1593, pp. 964–972.

[33] E. Jovanov, D. Starčević, A. Samardžić, A. Marsh, and Ž. Obrenović, "EEG analysis in a telemedical virtual world," *Future Generation Computer Systems*, vol. 15, no. 2, pp. 255–263, 1999.

[34] J. Thompson, J. Kuchera-Morin, M. Novak, D. Overholt, L. Putnam, G. Wakefield, and W. Smith, "The Allobrain: an interactive, stereographic, 3D audio, immersive virtual world," *Int. J. Human-Computer Studies*, vol. 67, no. 11, pp. 934–946, 2009.

[35] T. Nasir, "Geo-sonf: Spatial sonification of contour maps," in *IEEE International Workshop on Haptic Audio visual Environments and Games (HAVE'09)*, 2009, pp. 141–146.

[36] N. Schaffert, R. Gehret, A. O. Effenberg, and K. Mattes, "The sonified boat motion as the characteristic rhythm of several stroke rate steps," in *World Congress of Performance Analysis of Sport VII*, Magdeburg, Germany, 2008.

[37] N. Schaffert, K. Mattes, and A. O. Effenberg, "A sound design for the purpose of movement optimisation in elite sport (using the example of rowing)," in *Proceedings of the 15th International Conference on Auditory Display (ICAD2009)*, Copenhagen, Denmark, 2009.

[38] N. Schaffert, K. Mattes, S. Barrass, and A. O. Effenberg, "Exploring function and aesthetics in sonifications for elite sports," in *Proceedings of the Second International Conference on Music Communication Science*, Sydney, Australia, 2009.

[39] N. Schaffert, K. Mattes, and A. O. Effenberg, "Listen to the boat motion: acoustic information for elite rowers," in *Proceedings of the 3rd International Workshop on Interactive Sonification (ISon 2010)*, Stockholm, Sweden, 2010.

[40] E. Childs and V. Pulkki, "Using multi-channel spatialization in sonification: a case study with meteorological data," in *Proceedings of the 9th International Conference on Auditory Display (ICAD2003)*, Boston, MA, USA, 2003.

[41] C. Harding, I. A. Kakadiaris, and R. B. Loftin, "A multimodal user interface for geoscientific data investigation," in *Advances in Multimodal Interfaces – ICMI 2000*. Springer Berlin / Heidelberg, 2000, vol. 1948, pp. 615–623.

[42] C. Harding, I. A. Kakadiaris, J. F. Casey, and R. B. Loftin, "A multi-sensory system for the investigation of geoscientific data," *Computers & Graphics*, vol. 26, no. 2, pp. 259–269, 2002.

[43] B. Fröhlich, S. Barrass, B. Zehner, J. Plate, and M. Göbel, "Exploring geo-scientific data in virtual environments," in *Proceedings of the conference on Visualization '99: celebrating ten years*, San Francisco, CA, USA, 1999.

[44] S. Barrass and B. Zehner, "Responsive sonification of well-logs," in *Proceedings of the 6th International Conference on Auditory Display (ICAD2000)*, Atlanta, GA, USA, 2000.

[45] K. Beilharz, "(Criteria & aesthetics for) Mapping social behaviour to real time generative structures for ambient auditory display (interactive sonification)," in *INTERACTION - Systems, Practice and Theory: A Creativity & Cognition Symposium, Creativity and Cognition Press, The Dynamic Design Research Group*, Sydney, Australia, 2004.

[46] ——, "Gesture-controlled interaction with aesthetic information sonification," in *Proceedings of the second Australasian conference on Interactive entertainment*, Sydney, Australia, 2005.

[47] ——, "Wireless gesture controllers to affect information sonification," in *Proceedings of the 11th International Conference on Auditory Display (ICAD2005)*, Limerick, Ireland, 2005.

[48] ——, "Responsive sensate environments: past and future directions," in *Computer Aided Architectural Design Futures*. Springer Netherlands, 2005, pp. 361–370.

[49] A. C. G. Martins, R. M. Rangayyan, L. A. Portela, E. A. Junior, and R. A. Ruschioni, "Auditory display and sonification of textured images," in *Proceedings of the 3rd International Conference on Auditory Display (ICAD96)*, Palo Alto, CA, USA, 1996.

[50] R. M. Rangayyan, A. C. G. Martins, and R. A. Ruschioni, "Aural analysis of image texture via cepstral filtering and sonification," in *Proceedings of SPIE: Visual Data Exploration and Analysis III*, 1996.

[51] A. C. G. Martins and R. M. Rangayyan, "Experimental evaluation of auditory display and sonification of textured images," in *Proceedings of the 4th International Conference on Auditory Display (ICAD97)*, Palo Alto, CA, USA, 1997.

[52] A. C. G. Martins, R. M. Rangayyan, and R. A. Ruschioni, "Audification and sonification of texture in images," *Journal of Electronic Imaging*, vol. 10, no. 3, pp. 690–705, 2001.

[53] B. N. Walker and G. Kramer, "Mappings and metaphors in auditory displays: an experimental assessment," in *Proceedings of the 3rd International Conference on Auditory Display (ICAD96)*, Palo Alto, CA, USA, 1996.

[54] B. N. Walker, G. Kramer, and D. M. Lane, "Psychophysical scaling of sonification mappings," in *Proceedings of the 6th International Conference on Auditory Display (ICAD2000)*, Atlanta, GA, USA, 2000.

[55] B. N. Walker and D. M. Lane, "Psychophysical scaling of sonification mappings: a comparison of visually impaired and sighted listeners," in *Proceedings of the 7th International Conference on Auditory Display (ICAD2001)*, Espoo, Finland, 2001.

[56] B. N. Walker, "Magnitude estimation of conceptual data dimensions for use in sonification," *Journal of Experimental Psychology: Applied*, vol. 8, no. 4, pp. 211–221, 2002.

[57] B. N. Walker and G. Kramer, "Mappings and metaphors in auditory displays: an experimental assessment," *ACM Transactions on Applied Perception*, vol. 2, no. 4, pp. 407–412, 2005.

[58] B. N. Walker, "Consistency of magnitude estimations with conceptual data dimensions used for sonification," *Applied Cognitive Psychology*, vol. 21, pp. 579–599, 2007.

[59] N. Bearman and A. Lovett, "Using sound to represent positional accuracy of address locations," *The Cartographic Journal*, vol. 47, no. 4, pp. 308–314, 2010.

[60] P. Eslambolchilar, A. Crossan, and R. Murray-Smith, "Model-based target sonification on mobile devices," in *Proceedings of the 1st International Workshop on Interactive Sonification (ISon 2004)*, Bielefeld, Germany, 2004.

[61] M. Eriksson and R. Bresin, "Improving running mechanics by use of interactive sonification," in *Proceedings of the 3rd International Workshop on Interactive Sonification (ISon 2010)*, Stockholm, Sweden, 2010.

[62] T. Hermann, P. Meinicke, H. Bekel, H. Ritter, H. M. Müller, and S. Weiss, "Sonifications for EEG data analysis," in *Proceedings of the 8th International Conference on Auditory Display (ICAD2002)*, Kyoto, Japan, 2002.

[63] P. Meinicke, T. Hermann, H. Bekel, H. M. Müller, S. Weiss, and H. Ritter, "Identification of discriminative features in the EEG," *Intelligent Data Analysis*, vol. 8, no. 1, pp. 97–107, 2004.

[64] T. Hermann, G. Baier, and M. Müller, "Polyrhythm in the human brain," in *Proceedings of the 10th International Conference on Auditory Display (ICAD2004)*, Sydney, Australia, 2004.

[65] G. Baier and T. Hermann, "The sonification of rhythms in human electroencephalogram," in *Proceedings of the 10th International Conference on Auditory Display (ICAD2004)*, Sydney, Australia, 2004.

[66] G. Baier, T. Hermann, S. Sahle, and U. Stephani, "Sonified epileptic rhythms," in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*, London, UK, 2006.

[67] G. Baier, T. Hermann, and U. Stephani, "Event-based sonification of EEG rhythms in real time," *Clinical Neurophysiology*, vol. 118, no. 6, pp. 1377–1386, 2007.

[68] ——, "Multi-channel sonification of human EEG," in *Proceedings of the 13th International Conference on Auditory Display (ICAD2007)*, 2007.

[69] T. Hermann, G. Baier, U. Stephani, and H. Ritter, "Vocal sonification of pathologic EEG features," in *Proceedings of the 12th International Conference on Auditory Display (ICAD2006)*, London, UK, 2006.

[70] ——, "Kernel regression mapping for vocal EEG sonification," in *Proceedings of the 14th International Conference on Auditory Display*, Paris, France, 2008.