Reflecting on qualitative and quantitative data to frame criteria for effective sonification design

Katharina Groß-Vogt*
vogt@iem.at
(1) Institute of Electronic Music and Acoustics, University of Music and Performing Arts Graz
Graz, Austria

Kajetan Enge
kajetan.enge@fhstp.ac.at
Institute of Creative Media Technologies, St. Pölten University of Applied Sciences
St. Pölten, Austria

IOhannes m. zmölnig
zmoelnig@iem.at
(1)
Graz, Austria

Figure 1: Our four suggested criteria for effective sonification design.

ABSTRACT

A subjective stagnation in the field of sonification research has been discussed. However, sonification has spread in simpler forms. We present a data set from Google scholar that provides insights into the state of sonification research. Based on these data, the literature, and a small expert poll, we propose criteria for effective sonification design: the use of easily perceptible sounds, that are mapped naturally, do not contradict the data metaphor, and are appropriate to the task. A quantitative analysis of the data found no correlation between effective sonifications and the number of citations or the year of their publishing.

CCS CONCEPTS

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; • **Applied computing** → **Sound and music computing**.

KEYWORDS

auditory display, sonification, sonification design

ACM Reference Format:
Katharina Groß-Vogt, Kajetan Enge, and IOhannes m. zmölnig. 2024. Reflecting on qualitative and quantitative data to frame criteria for effective sonification design. In *Audio Mostly 2023 (AM '23), August 30-September 1, 2023, Edinburgh, United Kingdom.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3616195.3616233

*The first two authors contributed equally to this research, the third author contributed to the data collection and analysis.

AM '23, August 30-September 1, 2023, Edinburgh, United Kingdom

ACM ISBN 979-8-4007-0818-3/23/08.
https://doi.org/10.1145/3616195.3616233

1 INTRODUCTION AND RESEARCH QUESTIONS

Sonification research has been established in the last 20 years, but researchers have expressed their disappointment for the subjective stagnation in the field. For instance, Neuhoff [23] questioned if sonification is "doomed to fail". One reason he argues is that *"sonification is more often viewed by the public as an entertaining curiosity than as a scientific tool for understanding data"*, and he still misses the "killer app" [26]. On the contrary, Nees [21] concentrated on a handful of successful, i.e. ubiquitous, examples where sonification "works", such as alarms, even if these were mostly not developed within systematic sonification research.

Apart from the pure functionality of conveying information through non-speech audio, further added values of sonification have been mentioned throughout the literature. For instance, Ballora [2] discussed the 'wow' effect of sonification, and stated that *"sonification's potential value, like much of the scientific visualisation content, probably lies less in hard facts and more in how it may serve as a stimulant for curiosity."* Similarly, Neuhoff, in the above cited critical position paper, indicated some aspects that point towards the main point of our paper. For instance, *"most sonifications in widespread use today are simple binary messages,"* and explaining partly the reasons for this, he draws from his own research experience: *"a better approach to parameter mapping might be assigning data variables to acoustically complex but ecologically simple sounds (e.g., footsteps) that indicate changes in sounding objects or events"*. Finally, he asks, "is the killer app the appropriate metric by which we should measure the success of sonification?".

Our personal motivation for this paper is the - often inherent - promise of sonification as a problem-solver for the analysis of complex and/ or multivariate data. This promise is generally backed up by the great capabilities of human auditory perception. Still, no successful and widely-spread applications have been developed, no "killer app", even if both the necessary equipment (hard-, software)

and expertise (sound computing) have been at hand for the last twenty years. While we did not see a wide-spread application for exploratory data analysis, sonification has spread mostly in simpler forms, in, e.g., multimedia applications, monitoring environments, artistic works, and didactical or generic examples that demonstrate sonification itself.[1]

Therefore, we reasoned if and why "simpler" sonifications are more widespread. The added value of such sonifications is often not an enhanced functionality as compared to standard visualizations or artificial intelligence, but rather can be covered by terms such as affective design, engaging technologies, or, generally, embodiment. Subjectively, we see a tendency in auditory display research towards relatively simple sonifications. Certainly, the still sought-after design criteria could be based more easily on simple sonifications than on individual design solutions of complex tasks and data sets.

In this paper, we come back to Neuhoff's question, how to measure success of sonifications. Therefore we posed the research questions, (a) based on a proposed set of design criteria, is there evidence that certain sonifications are more successful or evolve over time? An (b), based on the reflection of this analysis, can we establish design criteria for effective sonifications?

2 BACKGROUND

The underlying questions for our research concern the main benefits of sonification and how "good" sonifications sound like.

2.1 What do we need sonification for?

We are nowadays opposed to the emergence of AI into previously human-centric fields, such as data exploration or paper writing. Worrall [32] defends the general usefulness of sonification, whose putting in doubt he calls *"increasingly pertinent"*, while there is a profound *"difference between a conception of life merely in terms of information flow and data storage as might be imagined by the Cognitivists [...], and one in which mind, body, and (now technologically enhanced) consciousness play a fundamental role in active perception, knowledge acquisition, meaning-creation and decision making"*. This statement underlines the most useful role of sonification in a worldview of embodied cognition. In this regard, other authors have suggested specific benefits of sonifications. De Campo et al. [9] stated that interdisciplinary sonification projects *"often reap their benefits outside the agenda. This may sometimes simply be the result of spending longer time with data; it may also result from sonification being a means to cooperate below the threshold of stabilized knowledge. The allusive layer provides a setting for the renegotiation of tacit concepts in a conversational learning process"*. In such an embodied perspective of sonification research, we have to address aesthetics in the design process, as has been pointed out by Vickers et. al [28], which then enhances the benefits stated above, such as sonifications being *"sufficiently engaging to engender sustained attention"* [ibid].

Already in 1994, Kramer[18] listed affective and metaphorical associations as perceptual factors in sonification design. Authors from the fields of sonic interaction design or sound design have correctly highlighted the affective nature of sonifications (that are based on sound and our experience of music perception). For instance, Barrass [4] has stated that *"[s]ound is a naturally affective, aesthetic and cultural medium. The extension of the aesthetic turn to sonification could transform this field from a scientific curiosity and engineering instrument into a popular mass medium."*

2.2 Which sonifications work?

For newcomers, there are still no guidelines how to design an effective sonification [24]. As Vickers et. al [28] stated, [it]*"sounds so simple to say that good sonification design involves finding the right way to represent the kinds of data or facts that we wish to reveal, but the realisation of this ideal has proved problematic"*, and, on the contrary, *"[s]onification may be ineffective if the rendered sound appears arbitrary to the listener in relation to the underlying data."* In depth-interviews with sonification designers [24] pointed out a number of facts. One trivial insight is that simple sonification mappings work because of their ease of use. In the summary of the interviews' findings, the cited authors conclude on an effective design process that *"requires in-depth investigation of the data, the inclusion of the user in the design process, a valid number of iterations in choice of sonification technique, parameter mapping and sound design."*

Incorporating the semiotics of sound into research has been debated, though in the Sonification Theory Chapter of the Sonification Handbook [31] this aspect rather falls short. Perhaps, generally, these aspects are given too little attention in the design, for instance as Pirhonen et al. are cited in the same chapter: *"Empirical approaches [...] have been largely dominated by atheoretical, arbitrary sound design choices."* Similarly, in other papers it is argued in favor of using metaphoric and/ or ecological sounds in a direct or indirect way [17, 29]. Ferguson & Brewster [11] discussed perceptual congruency between data and sound dimensions based on previous works, e.g. [12]. They state that *"many of these data:sound mappings fail to account for the listener's mental model of how the data value should sound during sonification"*. The authors explore relationships between conceptual variables and psychoacoustic parameters (instead of simple acoustic parameters such as pitch or tempo), in order to expand the number of effective sonification parameters.

Even if we focus mainly on the scientific discourse here, we acknowledge as well the contribution of the arts. To start with, artistic papers are part of many sonification-related conferences. Vickers [27] has discussed that sonification, if it is sonification, is also music, (and vice versa). He further elaborated a sonification aesthetics with co-authors [28], pointing out that the *"design task then becomes about finding a suitable fit between communicational efficancy and appropriate aesthetic character"*.

2.3 Paper outline

Instead of proposing a pure position paper, we intended to follow a more systematic approach, incorporating qualitative and quantiative research methods, to further develop our concept of effective sonification design. We build our findings around a data set from Google scholar, drawn in January 2023. Based on this, we know

[1] A few subjective examples: Chris Chafe's work on the Brain Stethoscope, http://chrischafe.net/; the Podcast "Loud Numbers" on data sonifications, https://www.loudnumbers.net/sonification; a sonification of Trump's lies, http://www.stephenandrewtaylor.net/lie-sonification/lie-index.html; or the listening back add-on for browsers, https://addons.mozilla.org/en-US/firefox/addon/listening-back/.

the most frequently cited authors working in the field; we invited these experts in an anonymous poll to provide a statement on the success of simple sonifications. Based on their responses, we further sharpened our notion towards an effective sonification and searched for quantitative evidence in our data set.

Besides our framing of design criteria, the data set itself is a valuable contribution for anyone interested in assessing sonification research.

3 COLLECTION AND OVERVIEW OF DATA

Review papers on sonification research have been focusing on the study of the International Conference on Auditory Display (ICAD) [1, 5, 26]. We argue that this falls short as sonification is a method that shows up at various scientific communities.

3.1 Data set of most relevant sonification papers

Addressing our first research question, we are seeking to explore which type of sonifications might be more successful or evolving over time. Assessing quantitative data about the dissemination of any type of sonifications in general is a huge endeavour. Sonification applications are varied between scientific, musical, social media, or journalistic approaches, and applied applications in industry. A recent data compilation is the Data Sonification Archive, a curated set of (by July 2023) around 500 sonifications [25]. While this is an interesting data set, it has an intrinsic bias due to being curated. In an effort that would allow us to study a more complete and less human-biased data-set, we therefore only focused on scientific publications. This obviously limits the validity of our analysis. Furthermore, it follows scientometrics, measuring scientific output quantitatively, with all its specific drawbacks and flaws. Specifically, our measure of success is here the number of citations a paper reached.

We consider Google scholar to be the most general scientific search tool, that is neither focusing on specific scientific domains nor depending on the individual entry of content in scientific social media platforms. In the absence of better alternatives, we relied on it's efficacy. Google's search algorithm performs as a black box, but it has been shown that the main sorting factor for their ranking of papers is how often they have been cited [6]. In a first step, we probed searching for a variety of terms, always with the help of scrapers to get a full list of up to 1000 hits per search, with information on the number of citations the paper has reached. It proved to be more to the point to use an aggregated search term, and we ended up with "sonification, auditory display, audification, sonify". In the resulting list, all papers had a clear thematic focus on sonification research, which had not always been the case when the terms were searched for individually [2].

In a next step, the mostly but not fully automatic pulling down of abstracts for each paper was a tedious process. Out of these abstracts, we generated a list of keywords for each paper with the help of the recently hyped ChatGPT. Obviously, for true keywords a full text analysis would have been necessary, but could not be provided as pulling 1000 full text papers was not possible.

[2]There were only a handfull of exceptions, where papers were found that had nothing to do with our notion of sonification: sonification (also: sonication) is used as a term in biology where sound is used to change proteins; and auditory display is used as a term in biology, e.g. when studying the sounds of apes.

This process ended in a data set of 1000 papers, including

- their title,
- a website/URL (as referenced by Google scholar),
- author(s),
- publisher information,
- their google rank in our search,
- publication year,
- the number of citations;
- paper abstracts;
- and keywords generated from abstracts.

The data set has been published as Creative Commons Attribution 4.0 International at 10.5281/zenodo.8171076.

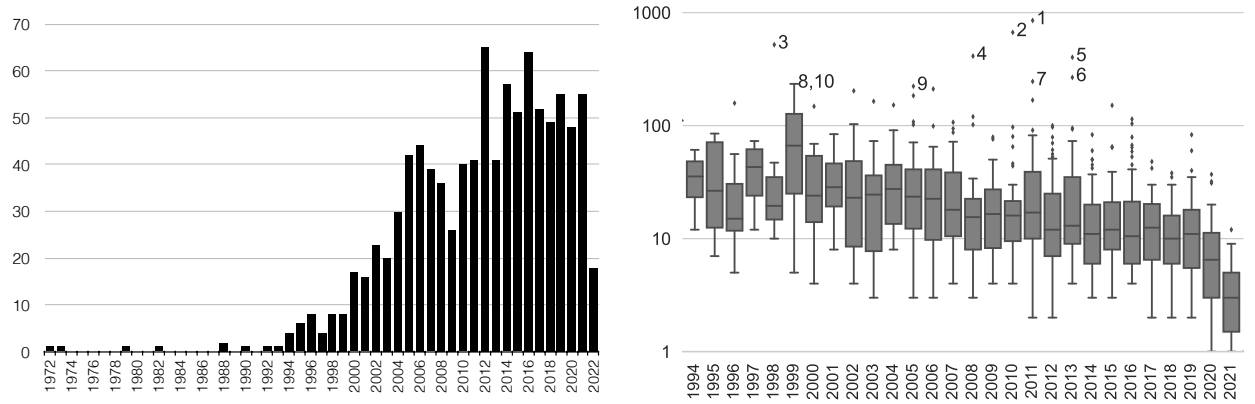
Fig. 2(a) shows the development of sonification research: single, early publications are multiplied from 1992 on, when the number of papers is rising until about 2005-2010; since then, the research output measured as number of publications stays rather constant. Fig. 2(b) shows a boxplot of the number of citations of the papers per year. The citations could be interpreted as a reception history of sonification. Individual, highly published papers lead to outliers, while the whole function is - of course - time-dependent. Early papers are cited over-proportionally while the last ten years evidently show a falling number. The top ten cited publications in our data set are mostly review papers or seminal books, with the exception of three methodological papers (numbers 3, 5, and 8 in Fig. 2(b)).

In a first, quantitative analysis, our data set already provides interesting aspects. We looked into the publishers' information to see where sonification research is published, see Fig. 3. The graphic shows various publishers, of which one fifth is ICAD.

Secondly, to get an overview of the topics treated within sonification research, we conducted a frequency analysis of all keywords (keep in mind that these are not "real" keywords but automatically generated ones out of the abstracts only). Only keywords with at least 3 mentions were taken into account; these were still 500 terms out of around 5000 generated from ChatGPT. Then, they were grouped (for instance, "blind" + "blindness" + "visually impaired" etc.) and categorized (e.g., "accessibility"). Generic words were ignored (such as, "sonification", "sound", "concept", etc.). Furthermore, many notions had to be omitted due to ambiguity - as one example, "performance" is both established as artistic practice and as users' ability in evaluations. For these reasons this overview is not a full keyword analysis. Though, the major research fields of sonification are represented, as shown in Fig. 4. For the following paper analysis, we focus on application papers only, i.e. the ones that describe a specific sonification design. This is, because we are interested in which sonifications are more successful than others. The most applied areas for sonification are movement, including sports or physiotherapy, and medicine.

3.2 Expert poll

Based on our preliminary data sets, we found a number of recent experts of sonification research: the first authors of the most cited papers since 2010, who have published more than once on "sonification" (one paper with at least 30 citations) or "auditory display" (one paper with at least 100 citations, as here the range of number of citations was much larger), and authors who had at least three publications since 2010 (for "sonification") counted as experts.



(a) Number of papers

(b) Number of citations per paper

Figure 2: Overview of the quantitative data set, the first 1000 hits of a Google scholar search for "sonification, auditory display, audification, sonify", conducted in January 2023. (a) shows the number of papers per year. (b) gives a boxplot of the number of citations per year and indicates the ten most cited papers:
1 - The sonification handbook (2011); 2 - Sonification report: Status of the field and research agenda (2010); 3 - Navigation system for the blind: Auditory display modes and guidance (1998); 4 - Taxonomy and definitions for sonification and auditory display (2008); 5 - Head-related transfer function and virtual auditory display (2013); 6 - A systematic review of mapping strategies for the sonification of physical quantities (2013); 7 - Theory of sonification (in: The sonification handbook; 2011); 8 - Listen to your data: Model-based sonification for data analysis (1999); 9 - Movement sonification: Effects on perception and action Using sonification (2005); 10 - Using sonification (1999).

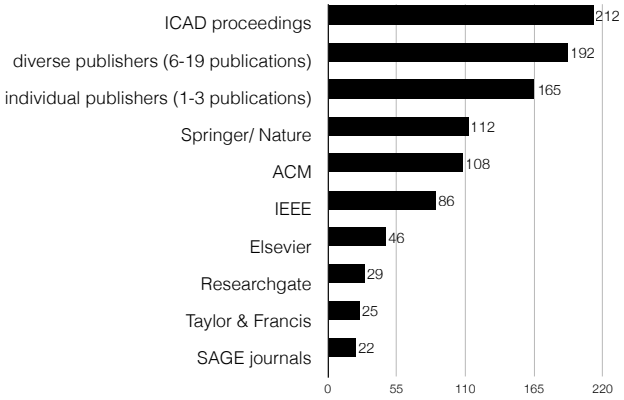


Figure 3: Publishers of sonification papers. Note that the list was automatically generated from the URL as provided by Google scholar, which sometimes refers to academic sites such as Researchgate instead of the initial publisher.

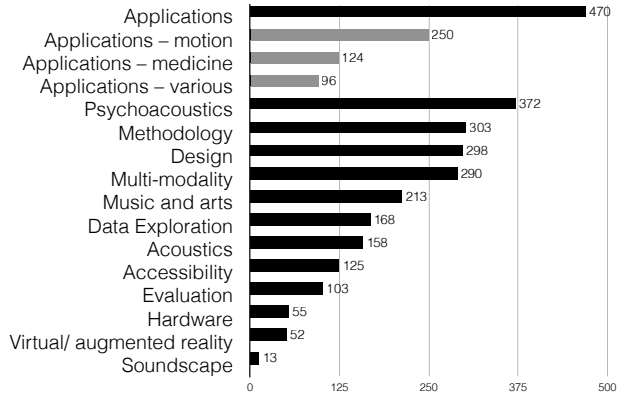


Figure 4: The frequency of categories, aggregated by hand out of the automatically found keywords.

These were asked in an expert poll in the form of an anonymous, open questionnaire on the internet. Of the whole 46 authors, 13 were not reachable, and out of the remaining 33, eight completed the survey.

At the time of the expert poll, we had only a preliminary idea of design criteria. We presented the experts with a (presumably) provoking statement on the success of simple sonifications in the general public. We defined what we meant by "simple" sonifications as (a) ones that have few mapping dimensions, which (b) lead to an easily understood sound design, and (c) employ salient sound features, and (d) ones that usually sonify small and/ or low dimensional data sets.

We asked for free comments on the topic addressing the following open questions: *Is "simplicity" defined clearly enough to delimit a field of research? Are „simple sonifications" really under-represented or under-valued at ICAD? Would it be helpful to look at them more*

closely? Or is the pursue towards the "killer app" - more complex sonifications with longer learnability, exploiting auditory perception at its full - still the way to go?

The introduction was piloted with our colleague as profound sonification expert before being sent out.

Following qualitative research standards we conducted inductive categorization [19] of topics raised by the experts: the answers were sliced into paragraphs, and each paragraph was annotated by three of the authors individually to distil their main idea. The individual findings were consensed, and gives a pattern of opinions.

The general attitude was positive and constructive, and all experts provided valuable comments. Three experts explicitly were fond of the initiative, i.e. bringing up this topic for discussion. Furthermore, one expert stated: *"I agree that the sonification community (from my experience) tends to overvalue exploratory/complex/aesthetic sonification projects that stray from the ideal goal of practical problem-solving."* (EX.4) The same expert still acknowledges the benefit of incorporating arts and designerly thinking into sonification research.

We saw that the short cover letter for the expert poll may have triggered misunderstandings. At least one expert thought we intended to do technically simple sonifications, for instance featuring sine tones, which is quite the opposite of our intent.

Our definition of simple sonification was criticized by half of the experts (i.e., four), and disadvantages of simple sonifications pointed out. For instance, simple mappings may fail to address the user experience after long term use. As one experts put it, *"simple sonifications are more easily digested at first listening and so lend themselves better to refereeing and conference presentation, but that does not mean complex sonifications are 'bad' - they just favour expert users who can appreciate all the subtleties of the sound."* (EX.5). This point is certainly true to some point, and possibly a general flaw in publishing scientific findings in a still young and diverse field such as sonification. Furthermore, two experts rightly pointed out that different sonifications have different goals, and two supported our arguments by bringing up even more added values of sonification, such as aesthetics, ecology, and affective effects.

Three experts stated that they thought the question was wrongly put, i.e. that differentiating between complex and simple sonifications was not valuable; rather, the context (e.g., users, tasks) should be taken into account. One of these three and one other expert generally disapprove of the idea of favouring simple sonifications, and espouse more the idea of the killer app or complex sonification. The general trend could be simplified as 3 in favour, 3 critical, and 2 opposed to the idea of studying simple sonifications (under the premise that there might have been misunderstandings about the concept).

Furthermore, two experts provided explicit examples for simple sonifications that we found well to the point: one is the variometer, an auditory display using beeps that increase in rapidity and pitch with increasing rate of airflow, e.g. used by glider pilots to monitor the rate of ascent or descent[3]; the second one a reduced musification of climate data, by the way illustrating that musifications can also be done effectively[4].

Topics that were brought up by one expert each were reasonings about the distinction between data and information, and psychoacoustic considerations of "simple" mappings. Finally, we would like to take up two open questions raised by experts: One is, if actually anyone has ever trained a complex sonification for a long time; at least, the designer(s) themselves. How would factors such as the learning curve or annoyance be evaluated after long-term use? Finally, one expert ended with *"final thought - if we don't know how to do simple then how can we do complex ?"* (EX.2)

We discussed the expert poll's results and sharpened our definition of notions further.

4 DEFINING EFFECTIVE SONIFICATION

The term effectiveness has been used in sonification research from the very beginning (see [31]), and was used in a way to reach the listeners and meet their goals. The authors of [24] recently discussed "effective methods" of designing sonifications. Effectiveness was also used in a specific sense within experimental studies or user tests, e.g. [14]. In another meaning of the word relating more to successful sonifications, Neuhoff [23] cites C. Scaletti for *"a major stumbling block to effective sonification design for the masses is a failure of designers to take the perspective of musically naïve and "non-attentive listeners".*

We also were inspired by the more established terms in the field of visualization and/ or design, for instance effectiveness, the appropriateness principle, and natural mapping[5]. A visualization is effective if it addresses the capabilities of the human visual system; and the appropriateness principle says that the representation used by the artifact should provide exactly the information acceptable to the task – neither more nor less. A potentially fruitful cross pollination between the fields of visualization and sonification is also shown by the theoretical constructs recently introduced by Enge et al. [10].

Within this paper we define effective sonification as a working definition to be further discussed in the respective communities.

```
  Effective sonification (see Fig.1)
(1) uses easily perceptible sounds that
(2) follow a natural mapping;
(3) they do not contradict the data metaphor and
(4) are appropriate to the task.
```

Effective sonifications can be based on any data sets, but their focus is less on exploring complex, high-dimensional data and more on communicating simpler data sets in an embodied way. Let's look at this in more detail:

(1) Effective sonifications use sounds that we can easily perceive as a result of our biological evolution or training. Therefore, a sine tone, even if easy to produce, can not be considered effective per se, as compared to harmonic sounds that are more ecologically valid. This criterion is also user-specific and depends on the individual and cultural training. Also, the listening context might play a role in making the sounds well heard, using salient sound features and avoiding masking effects. This first requirement is a basic psycho-acoustic one that should be self-evident for any sonification.

[3] https://www.youtube.com/watch?v=Ubc88NkWnN0
[4] https://www.youtube.com/watch?v=ONuA9HmkF3M

[5] For the meaning of these terms in their visual correspondences see https://infovis-wiki.net/wiki/Category:Glossary

(2) An effective sonification maps the data to sound properties in a way that the mapping is clear in terms of its polarity and estimated magnitudes, or at least general trends of the data - a natural mapping. If not based on well-known facts, these mappings should ideally be evaluated psycho-acoustically in pilot tests. Again, this criterion is a basic psycho-acoustic one, but already much more complex than the first one to achieve.
Even more extensive, in an ideal mapping, sound features are consistent with data features. We took up this point from the expert poll but acknowledge that not every effective sonification fulfills this correspondence condition of the data type (for instance, which psycho-acoustic parameter corresponds to interval data, such as temperature, i.e. ordered data with zero point?).
Note that it is evident that any sonification mapping has to follow a systematic approach as demanded by Hermann [15].

(3) Importantly, effective sounds should be true to the data, i.e. arising metaphors and emotions must at least not contradict the content of the data set. For example, many basic musifications employ instrumental sounds that infer pleasant music listening, while the data on which they are based contain abstract, neutral, or for instance, depressing information. In [24], one expert states that for sonifying rain data, *"you should hear that as the amount of rain, not the pitch of a Cello"*. For abstract data or those with no sound reference, the sonification designer must select a sound, recognizing that rarely it is perceived as neutral. For instance, when opposing audiolaypeople to abstract sounds, we have witnessed an overload; on the one hand people often lack experience in reduced listening [8], and on the other hand they associate "strange" new music or film sounds. Therefore, the mental model of the listener has to be taken into account and the sound design carefully chosen.

(4) Effective sonifications also need to consider the context. This is a long-demanded condition that was clearly elaborated by Barrass in his TaDa [3], task-oriented and data-sensitive method for auditory information design. The perspective has to be a user-centered one. In the same time, the sounds have to be appropriate in the sense of giving the relevant information, and only the relevant information. Using music for sonification can be justified, for instance, when motivating people for movements. Though, adding a full music track, and changing only one small aspect of it, might be an information overload that is not appropriate for an effective sonification task.

Effective sonifications can be based on any data sets. For small or low-dimensional data sets, simple sonifications still provide value to the listener compared to standard visualizations or text reading. This benefit can be measured in terms of improved comprehension, or any embodied quality such as affective reactions or engagement with the data, as has been discussed in the background section.

5 EXPLORING EFFECTIVE SONIFICATION IN THE DATA

5.1 Data tagging and analysis

For going more into depth with the quantitative data set of Google scholar, we manually worked through parts of it. We decided to tag papers of applied sonifications, with their category, domain science or central topic, intent (artistic, scientific, or mixed/unclear), their sonification method and rate them on a scale from 0.0 for "complex" sonifications and 1.0 for "effective" sonifications (i.e., assigning an "effectivity index" for each relevant paper). Two of the authors worked individually and compared their assessments of 110 randomly chosen, and partly anonymized, papers from the database. We hypothesized there could be correlations between our mean effectivity index and either the number of citations (giving a measure of "success" of effective sonifications) or the year of publishing (showing a temporal evolution in the sonification community, e.g. towards more effective sonifications). From the initial 110 papers, only around 40 remained in the analysis, after sorting out irrelevant papers (mainly, the ones not describing specific sonification applications, and some providing insufficient information on the sonification design).

Statistical analysis of these remaining papers employing Kendall's tau for the rank correlation coefficient revealed no significant correlations, neither with citation number nor publication date. We discussed two reasons for not finding quantitative evidence in our approach: presumably, there are factors influencing the number of citations more than our measure of effectivity; such as the general topic of the paper (medicine, sports, etc.), the medium where the paper is published, or the year of publication. Furthermore, the lack of a substantial number of papers that could be taken into account, and the subjective rating of the authors could be cited as methodological weaknesses.

We also did not find correlations between our effectivity index and the year of publication. While the same methodological flaws have to be acknowledged, one could argue that effective sonifications have been there from the beginning of sonification research until nowadays, but their frequency did not change significantly. This supports some of the discussed arguments in the background section, for instance the lack of design guidelines for newcomers to sonification. We still see "ineffective" sonifications being presented at conferences every year.

5.2 Examples of effective sonification designs

The randomly chosen and annotated paper data allowed us to draw qualitative conclusions, and we decided to look into the highest rated papers as best practice examples. This results in a random list of examples for effective sonification designs. We shortly discuss six papers [7, 13, 16, 20, 22, 30] that were rated high by both authors, in alphabetical order.

Blanco et al. [7] use water ambience soundscapes to monitor heart activity and timbre morphing sonification to "quickly assess if an abnormality in terms of the frequency, rhythm or amplitude in the signal occurs." They describe their sonification design as providing metaphoric associations while only using sound when the heart beat diverges from a normal rhythm.

Francoise et al. [13] investigate the use of interactive sound feedback for dance pedagogy. They base their sonification on vocalizations of experts while dancers are moving, and derive a set of design guidelines for a dance pedagogy context. This approach is inherently effective, as the vocalizations of experts (presumably) contain many layers of tacit knowledge that can be intuitively understood. Though, it may be difficult to generalize their findings for various contexts and users.

Hermann et al. [16] use vowel sounds, i.e. highly known sounds that are perfectly distinguishable by the human auditory system, to convey information about EEG data. The vowels are directly parameterized by the data in a systematic way, and provide the great possibility to talk about the resulting sonifications, referring to specific parts of it. Furthermore, the metaphoric congruency between brain waves and vowels as basics of language seemed convincing to us.

Minghim et al. [20] is an early work from 1995 with respectively limited means for generating sound and equally limited knowledge of psychoacoustics in general, as the authors state themselves. No sound files are available from the time. Still, the paper describes the use of metaphorical sounds to sonify surface data visualizations, and thus received a high effectivity score.

Neubauer et al. [22] use closed-loop feedback to support people with chronic pain. The sonification design is musically-informed, but rather neutral and appropriate to the task (not using more musical elements than are directly linked to the events of interest).

Vogt et al. [30] developed a metaphorical sonification for physiotherapy. The idea of the described sonification is to motivate patients in tedious physiotherapeutic trainings with music and nature sounds, link the mapping naturally to the movements, and use the sounds to give feedback about the correctness of the movements.

The list of the above presented examples is the result of an objective process, and the authors had no direct control on which papers were chosen as best practice examples. The result of best-scoring papers gives some insights, as our definition of effective sonification seems to favour a few approaches. For instance, the use of vowels as understandable psychoacoustic parameter that can be communicated well; this is another confirmation that effective sonification should be based on psycho-acoustic rather than acoustic parameters). Furthermore, the linking of movement and musical feedback is obviously fruitful, supporting on the one hand the importance of interactive sonification; on the other hand, the usage of the close bonding between music listening and moving, as has been long established in musicology research (for instance, see [33]), is truly effective. Blanco et al.'s contribution [7] is an ideal example of effective sonification using well-known sounds, that fit well to the data metaphor, and mapping them carefully.

6 CONCLUSION AND OUTLOOK

This paper intended to frame the criteria for "effective sonification design" in an objective process, incorporating qualitative data from experts and quantitative data from Google scholar. The quantitative data are limited to academic sonification, but we argue that this data set still provides an interesting perspective to the state and development of sonification design. Furthermore we collected opinions from experts in the field and used their comments to frame our notion of effective sonification design.

We have defined effective sonification as using easily perceptible sounds that follow a natural mapping; they do not contradict the data metaphor and are appropriate to the task. Correlating a qualitatively assigned effectivity index with the number of citations or years did not lead to significant results. It could be argued that the criteria are still not clear enough, or the chosen method is not applicable. Still, we believe that our chosen measure of success, i.e. the number of citations of a paper, is probably highly influenced by other factors and therefore does not show a correlation. When looking into the evolution of the effectivity index over years, our subjective assessment was confirmed: still, non-effective sonifications are published every year, possibly due to missing design frameworks and the high fluctuation of newcomers in the field.

One critial issue with our third criteria, not to contradict the data metaphor, is that not every data has a clear metaphor at hand; still, as the example of Hermann et al. [16] shows, mapping EEG data to vowels is not a 1:1 congruence but still effective. Furthermore, we have shown in previous work that domain scientists are sometimes astonishingly good at finding audio metaphors for their abstract data [29]. There seems to be a consensus in the sonification community that user-based design is the way to pursue, even if many sonifications do not meet this standard.

As result of our qualitative and quantitative process, framing the term effective sonification design, we propose a checklist for evaluating sonification designs that we intend to develop further:

(1) are the sounds used based on psycho-acoustic parameters?
(2) is the systematic mapping of data to sound features based on established knowledge (e.g., experiments for polarity or magnitude estimation), or has it been proven in pilot experiments?
(3) does the final sound invoke metaphors and emotions that support the semantics of the data?
(4) is the sonification appropriate for the defined task and users, without adding additional layers of meaning?

As a final remark we would like to encourage everyone publishing sonification research to clearly state in your publications which sonification methods you used, which sound mapping, and why you chose it. Most papers we analyzed failed to give enough details of the actual sonification design.

We hope that this paper will serve as a starting point for a fruitful discussion and help to set up standards for effective sonification design.

ACKNOWLEDGMENTS

Thanks to the experts in the expert poll for their feedback. This research was funded in part by the Austrian Science Fund (FWF): P33531-N and the Gesellschaft für Forschungsförderung Niederösterreich (GFF) SC20-006.

REFERENCES

[1] Areti Andreopoulou and Visda Goudarzi. 2021-06. Sonification First: The Role of ICAD in the Advancement of Sonification-Related Research. In *Proceedings of the 26th International Conference on Auditory Display (ICAD 2021)* (Virtual

Conference). International Community for Auditory Display, 65–73. https://doi.org/10.21785/icad2021.031
[2] Mark Ballora. 2014-04. Sonification, Science and Popular Music: In Search of the 'Wow'. 19, 1 (2014-04), 30–40. https://doi.org/10.1017/S1355771813000381
[3] Stephen Barrass. 1997. *Auditory Information Design*. phdthesis. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.127.6228
[4] Stephen Barrass. 2012-05. The Aesthetic Turn in Sonification towards a Social and Cultural Medium. 27, 2 (2012-05), 177–181. https://doi.org/10.1007/s00146-011-0335-5
[5] Nick Bearman and Ethan Brown. 2012. Who's Sonifying Data and How Are They Doing It? A Comparison of ICAD and Other Venues since 2009. In *Proceedings of the 18th International Conference on Auditory Display* (Atlanta, GA, USA). International Conference on Auditory Display.
[6] Jöran Beel and Bela Gipp. 2009. Google Scholar's Ranking Algorithm: An Introductory Overview. In *Proc. of the 12th International Conference on Scientometrics and Informetrics (ISSI'09)* (Rio de Janeiro (Brazil)), Vol. 1. International Community on Auditory Display, 230–241.
[7] Andrea Lorena Aldana Blanco, Steffen Grautoff, and Thomas Hermann. 2016. Heart Alert: ECG Sonification for Supporting the Detection and Diagnosis of ST Segment Deviations. In *5th Interactive Sonification Workshop (ISon 2016)*.
[8] Michel Chion. 2012. The Three Listening Modes. (2012), 48–53.
[9] Alberto de Campo, Julian Rohrhuber, Till Bovermann, and Katharina Gross-Vogt. 2023. Sonification and Auditory Display in Supercollider. In *To Be Published in: The SuperCollider Book*.
[10] Kajetan Enge, Alexander Rind, Michael Iber, Robert Höldrich, and Wolfgang Aigner. 2023-08-21. Towards a Unified Terminology for Sonification and Visualization. (2023-08-21). https://doi.org/10.1007/s00779-023-01720-5
[11] Jamie Ferguson and Stephen A. Brewster. 2018-04-21. Investigating Perceptual Congruence between Data and Display Dimensions in Sonification. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC Canada). ACM, 1–9. https://doi.org/10.1145/3173574.3174185
[12] Sam Ferguson, Densil Cabrera, Kirsty Beilharz, and Hong-jun Song. 2006. Using Psychoacoustical Models for Information Sonification. In *Proceedings of the 12th International Conference on Auditory Display* (London United Kingdom). International Community for Auditory Display.
[13] Jules Françoise, Sarah Fdili Alaoui, Thecla Schiphorst, and Frederic Bevilacqua. 2014-06-21. Vocalizing Dance Movement for Interactive Sonification of Laban Effort Factors. In *Proceedings of the 2014 Conference on Designing Interactive Systems* (Vancouver BC Canada). ACM, 1079–1082. https://doi.org/10.1145/2598510.2598582
[14] Florian Grond, Thomas Hermann, Vincent Verfaille, and Marcelo M Wanderley. 2010. Methods for Effective Sonification of Clarinetists' Ancillary Gestures. In *Gesture in Embodied Communication and Human-Computer Interaction: 8th International Gesture Workshop, 2009*. Springer, 171–181.
[15] Thomas Hermann. 2008-06. Taxonomy and Definitions for Sonification and Auditory Display. In *Proceedings of the 14th International Conference on Auditory Display (ICAD 2008)* (Paris, France). International Community for Auditory Display. http://hdl.handle.net/1853/49960
[16] Thomas Hermann, Gerold Baier, Ulrich Stephan, and Helge Ritter. 2008-06. Kernel Regression Mapping for Vocal EEG Sonification. International Conference for Auditory Display (ICAD).
[17] Peter Keller and Catherine Stevens. 2004. Meaning From Environmental Sounds: Types of Signal-Referent Relations and Their Effect on Recognizing Auditory Icons. 10, 1 (2004), 3–12. https://doi.org/10.1037/1076-898X.10.1.3
[18] Gregory Kramer. 1994. Some Organizing Principles for Representing Data with Sound. (1994), 185–221.
[19] Philipp Mayring. 1994. *Qualitative Inhaltsanalyse*. Vol. 14. UVK Univ.-Verl. Konstanz.
[20] R. Minghim and A.R. Forrest. 1995. An Illustrated Analysis of Sonification for Scientific Visualisation. In *Proceedings Visualization '95* (Atlanta, GA, USA). IEEE Comput. Soc. Press, 110–117. https://doi.org/10.1109/VISUAL.1995.480802
[21] Michael A. Nees. 2018-10. Auditory Graphs Are Not the "Killer App" of Sonification, But They Work. 26, 4 (2018-10), 25–28. https://doi.org/10.1177/1064804618773563
[22] Lilly Neubauer, Nicolas E Gold, Temitayo Olugbade, Amanda CdeC Williams, and Nadia Berthouze. 2021. Functional Musical Sonification for Chronic Pain Support. In *Ubiquitous Music*.
[23] John G. Neuhoff. 2019-06. Is Sonification Doomed to Fail?. In *Proceedings of the 25th International Conference on Auditory Display (ICAD 2019)* (Newcastle upon Tyne). Department of Computer and Information Sciences, Northumbria University, 327–330. https://doi.org/10.21785/icad2019.069
[24] Michael Quinton, Iain McGregor, and David Benyon. 2023. Investigating Effective Methods of Designing Sonifications. Proc. of the Interational Conference on Auditory Display (ICAD). https://doi.org/10.21785/icad2018.011
[25] Lenzi S., Ciuccarelli P., Liu H., and Hua Y. 2020. Data Sonification Archive. http://www.sonification.design
[26] Alexandra Supper. 2011-12-02. The Search for the "Killer Application": Drawing the Boundaries around the Sonification of Scientific Data. In *The Oxford Handbook of Sound Studies*, Trevor Pinch and Karin Bijsterveld (Eds.). Oxford University Press, 0. https://doi.org/10.1093/oxfordhb/9780195388947.013.0064
[27] Paul Vickers. 2016. Sonification and Music, Music and Sonification. In *The Routledge Companion to Sounding Art*. Routledge, 155–164.
[28] Paul Vickers, Bennett Hogg, and David Worrall. 2017. Aesthetics of Sonification: Taking the Subject-Position. In *Body, Sound and Space in Music and beyond: Multimodal Explorations*. Routledge, 89–109.
[29] Katharina Vogt and Robert Höldrich. 2010. A Metaphoric Sonification Method-towards the Acoustic Standard Model of Particle Physics. In *The 16th International Conference on Auditory Display (ICAD-2010)*. International Community for Auditory Display, Washington, D.C., USA.
[30] Katharina Vogt, David Pirrò, Ingo Kobenz, Robert Höldrich, and Gerhard Eckel. 2010. PhysioSonic - Evaluated Movement Sonification as Auditory Feedback in Physiotherapy. In *Auditory Display* (Berlin, Heidelberg), Sølvi Ystad, Mitsuko Aramaki, Richard Kronland-Martinet, and Kristoffer Jensen (Eds.). Springer Berlin Heidelberg, 103–120. https://doi.org/10.1007/978-3-642-12439-6_6
[31] Bruce N Walker and Michael A Nees. 2011. Theory of Sonification. In *The Sonification Handbook*. Vol. 1. Logos Verlag Berlin, 9–39.
[32] David Worrall. 2018-06. Sonification: A Prehistory. In *Proceedings of the 24th International Conference on Auditory Display - ICAD 2018* (Houghton, Michigan). The International Community for Auditory Display, 177–182. https://doi.org/10.21785/icad2018.019
[33] Agata Zelechowska, Victor Gonzalez Sanchez, and Alexander Refsum Jensenius. 2020-09-15. Standstill to the 'Beat': Differences in Involuntary Movement Responses to Simple and Complex Rhythms. In *Proceedings of the 15th International Audio Mostly Conference* (Graz Austria). ACM, 107–113. https://doi.org/10.1145/3411109.3411139

Received May 2023; accepted July 2023