Designing Sonification for an Interactive Multimodal Physics Simulation

A comparison and evaluation of continuous and discrete sonification in an educational physics simulation

Master Thesis

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STUDENT REPORT

Abstract:

This thesis provides an overview of sonification, relevant sonification theory, and different applications. Specifically, it investigates interactive sonification, and aims to compare and evaluate a discrete vs. a continuous sonification in an interactive physics simulation. A design and implementation process of these two sonification instances is described, before conducting an experiment to measure user experience for the two cases. However, the results of the experiment (n=22) were not statistically significant (p=0.175), and therefore no conclusion with respect ot measured user experience can be made. However, qualitative results are still discusses, as well as limitations and future work.

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Preface

What does data *sound* like? When being introduced to the idea of expressing information through sound, it sounded almost mystical to me. My scientific background meant that visual graphs and plots were deeply ingrained in how I analyse and perceive scientific data, but how could this same information be represented by sound?

Of course after learning a bit more about sonification, I realised that there is nothing mystical about it. However, this did not make it any less fascinating to me. In fact, the more I learnt about it, the more I was convinced of the benefits of establishing it as an alternative to visual information, as a new way of learning and knowing.

My physics background from my undergraduate studies obviously makes me very interested in physics, as well as promoting physics engagement and interest in this field. It was therefore very natural for me to combine these interests with my interest in sound, to provide the foundation of this project.

Working with and designing an interactive sonification has been a very rewarding experience for me. It has made me think about how sound shapes so many of our daily experiences, and how pretty much every action also has a sound output that provides us with information. It has made me think about how the pitch changes when filling a kettle with water tells me when to stop the water, or how the pitch and amplitude of a waterdrop hitting a surface immediately tells me something about its size and the speed it was falling at. Trying to utilise this intimate relationship between sound and action in an auditory interface has been a challenging, but fun task, but has provided me with a deeper insight into the power and complexity of our auditory system.

Aalborg University, September 11, 2019

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Chapter 1

Introduction

Presenting information and data through visual means such as graphs and plots is a very familiar idea, and we are used to efficiently analyse and obtain information through these visual tools. However, real world phenomena are not so exclusively visual, and a lot of the information we process from the real world is obtained through sound, by our very complex and sophisticated auditory system. In the relatively new (compared to its visual counterpart) field of auditory displays and sonification, information display through sound is the main motivator. Its researches examine how the human auditory system can be used as the primary information carrier for communicating information. [19]

Briefly put, sonification can be defined to be "the use of nonspeech audio to convey information". More specifically, "sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation". [26] This entails many different transformation methods from data to sound, and many different purposes for information communication and interpretation.

This thesis presents an overview of sonification theory and research, and then presents the design and implementation for two different sonification scenarios for an interactive multimodal physics simulation, one in which the auditory information display is continuous, and one in which it is discretized. The main research goal is to investigate which of enhances user experience the most. An experiment consisting of a questionnaire will be carried out, and the results evaluated and discussed. Lastly, directions for future work is outlined.

The structure of the specific chapters is as follows: chapter 2 gives a general introduction to the topic, discussing the historical background, the motivation for using sonification, and gives an account of sonification today. Special attention is given to one of the uses of sonification today: sonification in learning and education. The chapter concludes with the formulation of the initial research goal and points to further research that needs to be done before beginning the design process.

The third chapter deals with sonification theory and taxonomy, giving formal definitions and categorizing different sonification methods, with the aim of creating terminology and a theoretical foundation for working with sonification. The last part of the chapter will discuss interaction in sonification. The auditory perception-action loop will be introduced, and different ways of introducing interaction in sonification will be outlined. and explains how this is important for the design and implementation of interactive sonification. Lastly, some research questions in the field of interactive sonification, and then finally, formalises the main research goal of the thesis in the form of a problem statement.

Following the problem statement, the design process of the different sonifications can begin. Chapter 4 explains how to different designs were made to facilitate investigation of the problem statement. It explains the choice of a physics simulation to sonify, and outlines the scientific model the simulation is expressing. Then the translation of these concepts into sound is explained.

Chapter 5 deals with the technical implementation of the sonification designs from the previous chapter. It describes the JavaScript framework the simulation is coded in, how the simulation was modified for the purpose of this thesis, and the additional scripts added to create the sonification.

Whereas chapter 5 deals with the algorithmic implementation of the sonifications, chapter **??** discusses the sounds used for the sonifications. It discusses some relevant issues in sonification aesthetics, and outlines the implementation two different aesthetic strategies for the sonification designs. A short user-survey is conducted, resulting in the final design of the sonifications.

Chapter 6 proposes a testing procedure to evaluate and compare the final designs, which is then conducted at an interactive science museum.

In chapter 7 the results from the 22 participants is presented and analysed, before discussing the results in chapter 7.

Finally, the research and work of the thesis is summarised before a conclusion is made in chapter 9. After this there are some reflections and final remarks from the author in 10, as well as some proposed directions for future work.

Chapter 2

An Overview of Sonification

This chapter aims at providing the reader with an overview of the field of sonification. Firstly, a brief historical account of sonification will be given, followed by a section discussing the motivation for sonification as a way of expressing information. Then the role of sonification and state of the art of the field will be outlined, which will naturally lead to a discussion of sonification in learning and applications of this. Following this the initial problem statement and direction for further research will be outlined.

2.1 History of Sonification

There are examples of sonifications that predate the term itself. Examples of this include familiar devices such as the Geiger counter and the sonar, the auditory thermometer, and numerous medical devices and devices used for navigation. [26] Another, more recent example with more advanced sonification is the software designed by Lunney and Morrison [29] in 1990, designed to enable blind chemists to examine infrared spectrographic data by auditory presentation.

There are many other instances similar to this. Nevertheless, sonification as a field of research did not emerge until 1992, when the International Community for Auditory Display (ICAD) was formed. This marked the beginning of a systematic formalisation of sonification and the areas of interest relevant to it. [19]

Some of the first works of literature aiming to define and expand on these previously undefined concepts of sonification can be found in the proceedings of the first ICAD conference from 1994. The proceedings included papers on designing auditory interfaces for blind users [11], the perception of virtual auditory shapes [21], as well as how to use spatialization techniques in auditory displays [48], [1], all representative of issues still relevant in the field today. The collection of proceedings to this conference every year from then on now constitute an extensive overview of the issues and theory present in the field. The papers are all freely available under the Georgia Tech SMARTech repository today[1].

In addition to this, there are a few overviews aimed at creating a common framework of sonifications that are worth mentioning. The first is the *Sonification Report: Status of the Field and Research Agenda* from 1997, written by Gregory Kramer et al. [26], whose authors and co-authors included many of the prominent sonification researchers at the time. This report is an overview of sonification research outlining the work so far as well as proposed directions for future work, and can be seen as the first work aimed at creating some common guidelines for sonification and combining them in a report.

Another notable work is *The Sonification Handbook*, which is a comprehensive presentation of key research areas relevant to the field of sonification. It was published in 2011 and is edited by Thomas Hermann, Andy Hunt, and John G. Neuhoff [20], with various authors contributing to the different chapters of the book. It is by far the most extensive single piece of work dedicated to the field of sonification so far, and is an incredibly valuable resource for anyone looking into this field. Its introduction and first chapter, which include definitions and background theory has been the starting point of the theoretical foundation of this thesis, and many of the chapters serve as important references for specific sonification topics.

2.2 Why Sonification?

An interesting, and very important question to ask is why anyone would want to sonify data at all. There are many apparent reasons why it would be simpler to just use visualization techniques to represent data, such as users' familiarity with visual displays, the many and well tested visualization techniques available, and the ease at which they can be produced. [19] However, there are numerous reasons why understanding data with the use of our auditory system can in many cases be a good idea.

2.2.1 The Power of Our Auditory System

One of the main motivations for using sound to communicate data rests on the recognition of the power and complexity of our auditory system and the wish to utilise this to communicate information.

First of all, one interesting feature of our auditory system is the ability to distinguish between different streams of sound and also selectively focus on individual streams, also known as the "cocktail party effect". [35] This means that we are also able to single out and focus on a specific sound in a complex auditory scene, such as at a concert. This attentive focus our auditory system can perform is something that is still not completely understood, but it certainly provides possibilities when

[1] https://smartech.gatech.edu/handle/1853/49750

designing auditory interfaces. It provides the possibility of expressing multidimensional data with different sound streams, and the auditory system will be able to focus on individual streams or dimensions, as well as the collective progression.

The perception of rapid temporal variation is also a feature where our auditory system excels. Sound is a temporal phenomenon that is based on rapid changes over time, and the purpose of our auditory system is then to understand these changes. [35] This auditory sensitivity to temporal change makes it an excellent choice for interpreting phenomena or data that is changing rapidly over time, and to recognise dynamic patterns. In [7], Carla Scaletti even argues that the tendency to communicate phenomena that are dynamic with static visual graphs even biases our world view, whereas auditory representations have the potential to exhibit the true, dynamic nature of these phenomena.

Auditory scene analysis and the perception of temporal variation are often highlighted as two of the most important advantages of using sound to express information. However, there are many secondary features that are also useful. For example, our auditory system is capable of interpreting sounds using multiple layers of understanding. If we take the example of some spoken words; first of all, we are able to understand the meaning of the words, but we also detect various other information, such as the gender, age, and emotional state of the speaker, to name a few. [19]

Another interesting quality is our ability to extract detailed information about sounds we are familiar with. An illustrating example given in the introductory chapter of *The Sonification Handbook*, is the sound of a faulty car engine. In this case, an untrained listener may be able to tell that something if off. However, a professional car mechanic that has been exposed to maybe hundreds of faulty engines and experienced their corresponding sound, might be able to tell exactly what is wrong with the engine just by listening to the sound it makes. This highlights the potentiality of our auditory system to quickly and accurately extract information if trained to do so. Extending this to auditory interfaces, it is possible to efficiently communicate very detailed information with just a little training.

Moreover, unlike visual information, auditory information does not require the listener to face the display to attain information. Auditory information can therefore be useful when our eyes are occupied with something else.

This list gives some insight into the many features exhibited by our auditory system, but is not an exhaustive list. All in all, it is clear that the auditory system demonstrates many sophisticated and useful features that can be utilised to communicate information through sound.

2.2.2 Accessibility

Another important argument for using sound to express information, is accessibility. A lot of the information that is available to us is perceived through vision.

However, as mentioned above, sound also has the ability to communicate detailed and colourful descriptions of the world around us. This is perhaps even more true for people who because of some kind of disability, rely more on their audition. Consequently, sonification provides the opportunity for these people in particular to extract important information not available to them through sight.

There is a chapter dedicated to this topic in *The Sonification Handbook*, which discusses many of the relevant issues when designing auditory interfaces for visually disabled people. [33]

There are many examples of sonification being used in assistive technology. One idea is that of "Soundgraphs", first introduced in 1985 [30]. The concept of soundgraphs is that Cartesian graphs are represented by changes in the pitch of a sound corresponding to the height. Soundgraphs have later been implemented by various researchers in different forms, see for example [6] and [15].

A recent success story that found its way to the public through both a TED talk[2] and magazine articles [3,4], is that of the blind astronomer Wanda Diaz-Merced who uses sonification software to analyse astronomical data for her research. In her doctoral thesis [28] she presented research on the use of sound to explore and analyse signals in space physics data using her own proposed sonification technique, and evaluated the technique through experimentation. She investigated whether sonification, when in combination with data visualisation, would increase sensitivity to details in the data masked by noise. The results, as well as her own reported experience with using it for research, point to positive results, with sonification increasing perception of the data. [27]

The full potential of auditory displays in assitive technology remains unexplored, but definitely seems to have promising applications that will provide visually impaired with more opportunities when it comes to analysing and interpreting data.

2.2.3 Towards a Discipline of "Perceptualization"

As established, sonification is valuable because it can take advantage of the properties of our auditory system, or it can provide information in cases where visual information is inaccessible. However, another motivator is the idea that complementary information can provide deeper insights and different interpretations, which is valuable in itself. Our senses all deliver different types of information, and these types of information combined can provide a more complete picture of the data at interest.

[2] https://www.ted.com/talks/wanda_diaz_merced_how_a_blind_astronomer_found_a_way_to_hear_the_stars
[3] https://interestingengineering.com/blind-astronomer-found-way-hear-stars
[4] https://www.cbc.ca/news/canada/british-columbia/star-sounds-wanda-diaz-merced-ted-1.3452236

With the sonification of astronomical data from above, it was noted that some of Dr. Diaz-Merced's sighted colleagues who tried the sonification software for analysis, reported results and new patterns they had overlooked by simply looking at visual representations of the data, and her thesis provided further confirmation of this. [27], [28] This points to the conclusion that sonification should not only be utilised in isolation, or when it is the only option, but as a part of a multimodal representation of data that can lead to deeper, more detailed and accurate interpretations than we have had before.

The editors of *The Sonification Handbook* refers to this as a part of "*Perceptualization*", in which not only sound, but all of our perceptual capabilities are used to communicate information. They envision a future with a better balanced use of all the available modalities in order to interpret data. [19]

Not only is the technology required to generate and modify sonifications in real-time now available, today there is also an abundance of data being produced and an increasing need for means to effectively comprehend this data.[19] There is a growing appreciation of audition as not only being a "second cousin to vision, only to be brought into play when vision is unavailable or already overstrained", as Worrall puts it [12], but an important alternative to visual tools. Before us then lies an endless number of opportunities to fully investigate and realise the full potential of sonification as a method for learning and understanding.

2.3 Sonification Today

After the many good reasons for using sonification discussed above, it is natural to ask what is going on in the field today, and what it is actually being used for.

As mentioned, sonification was officially established as a field of research with the formation of ICAD in 1992. Since then, many different practitioners have contributed in various ways to the field. The annual ICAD conferences provide a platform dedicated solely to sonification and auditory displays, and contribute to an ever-expanding database of high-quality literature on sonification. However, ICAD is no longer the only initiative dedicated to sonification, and many other many other initiatives devoted to the topic have emerged in recent years.

One example of an affiliation exclusively committed to the research of sonification is the Georgia Tech Sonification Lab[5], which is a research group that specialize in multimodality and auditory interfaces, and much of their work focus on how auditory interfaces can be used by people with visual impairments. Some of their current work will be discussed in education section.

Another lab worth mentioning is the work of the Ambient Intelligence Group at the University of Bielefeld, which has produced important research in the field of sonification. An overview of their work can be found on their website[6].

Furthermore, sonification projects such as SysSon[7] created as a collaboration by the IEM, WegCenter, and SysMus Graz, aimed at introducing sonification to scientific fields, specifically climate science, have contributed with valuable research to the field.

There are also a number of sonification softwares out there, xSonify[8] a Java application to display numerical data as sound for analysis of space data developed by Diaz-Merced and collaborators, SoniPy[9], an open-source Python sonification framework, Sonification Sandbox[10], a Java program developed by the Georgia Tech Sonification Lab that converts datasets to sounds, among others.

The possible uses of sonification is many, and among many things, it can be used for medical diagnostic tools [25], sports and exercise monitoring [9], or various data analysis tasks [17]. There are many interesting implementations like these, but a complete discussion of the state of the art of sonification goes beyond the scope of this thesis, so now only sonification for the purpose of learning will be discussed.

[5]http://sonify.psych.gatech.edu/
[6]https://www.cit-ec.de/en/ami/sonification
[7]https://sysson.kug.ac.at/index.php?id=14007
[8]https://sourceforge.net/projects/xsonify/
[9]http://www.sonification.com.au/sonipy/index.html
[10]http://sonify.psych.gatech.edu/research/sonification_sandbox/index.html

2.4 Sonification in Learning

Because the essence of sonification is conveying information, with the possible side effects of increasing engagement, accessibility and understanding, its application in education seems obvious.

Sonification as a teaching tool in STEM (science, technology, engineering, and mathematics) education is particularly relevant, and numerous works have focused on sonification is such environments. So far, it seems to be possible to divide the sonifications made for education into two main categories: sonified graphs and interactive sonified simulations.

2.4.1 Sonified Graphs

"*Testing the effectiveness of sonified graphs for education: A programmatic research project*" by Bonebright et al. [4] is a study from 2001 aimed at investigating the effectiveness of the use of auditory graphs in education. The project consisted of three laboratory experiments: one which tested whether the participants could match auditory representations with their visual counterparts, one which tested whether the participant could better comprehend the data sets with the addition of sound, and one which investigated whether the participants would understand the sonified graphs better with practice. Results showed a high accuracy rate when matching the auditory to the visual graphs,....

A paper by Ballora et al. from ICAD 2018 investigated the use of sonification of earth science data for an undergraduate education course in oceanography. [3] Data sets including sets of the monthly mean numbers of sunspots, tide levels, and global mean sea levels were sonified and presented to the students. The students were asked to fill in questions regarding understanding of the material and connections between the data sets. The results of the study showed that a majority of the students found that the sonifications improved their understanding. Results also showed that the sonifications were especially successful in combination with visual graphs. The authors conclude that although the results are preliminary, they show promise for efficient communication of science through sound, and point to the promise of a more holistic science pedagogy that will be accessible to more students and provide thorough insights through hearing.

Another study from 2019 by Vines et al., investigated the use of sonification for STEM education in an open-learning environment [44]. Specifically, the aim was to assess the suitability of audio graphs as a teaching tool for non-sighted and sighted students. The authors pointed out that the electronic nature of sonification makes it suitable to use in virtual learning environments. The testing was performed in two stages: one with a small test group of participants, and one where the sonifications were deployed in a module at the virtual learning environment *Open University*. Results were mixed: whereas the first part of the test showed good results where the participants were able to use the sonifications to extract information, the second part consisted of mixed reviews, although some participants reported that the sonifications were an interesting learning method.

Other studies regarding the use and efficiency of auditory graphs for use in STEM education can be found in for example [43] and [10], and and summaries and design principles for auditory graphs can be found in [36] from 2005, and [46] from 2010.

2.4.2 Interactive Simulations

Sonification for the use in education does not necessarily need to be static auditory graphs. Interactive sonification is also of interest. An example of this is the sonified interactive simulations by PhET.

The PhET Interactive Simulations project[11] at the University of Colorado Boulder is an initiative that so far has produced more than 130 free science and mathematics simulations, that are currently being used in classrooms from elementary to university level. All the simulations are freely available on their website, and aims to create a an interactive learning experience to promote learning. So far has grown in popularity, with a reported 80 million online runs and downloads in 2014. [32] Moreover, the simulations are also open source to promote collaborative efforts, and all source code can be found on github[12].

So far, their simulations have relied mostly on visual representations. However, since 2014, an initiative was created to enhance the accessibility for students with disabilities, and one of ways accessibility is being improved is through sonification. [32] In addition to making the simulations more accessible to students with visual impairments, adding sonifications to the simulations will also serve to make the simulations more engaging, thus providing an overall better learning experience.

Papers on the process of sonifying PhET simulations can be found in [49], [42], [2].

Drawing inspiration from this, the PhET simulations provide a perfect medium for adding sonification to an interactive educational simulation, and to investigate aspects of sonification design and implementation.

[11] http://phet.colorado.edu/

[12] https://github.com/phetsims

Chapter 3

Theory of Sonification

In essence, sonification seeks to translate relationships in data or information[1] is communicated through non-speech sound. into sound(s) that exploit the auditory perceptual abilities of human beings such that the data relationships are comprehensible. As noted in [47], sonification involves elements of both science, which necessarily must be driven by theory; and design, which is not always scientific. This chapter is dedicated to sonification theory.

This aim of this chapter then, is to establish a theoretical framework for sonification. It will introduce relevant terminology and sonification taxonomy, and will review different ways of classifying sonifications. The purpose of this is to provide a thorough overview and understanding of sonification methods and functions. Lastly, interaction is sonification will also be discussed, before formulating the problem statement of this thesis.

3.1 Formal definition

An auditory display can be defined as any display in which sound is the medium used to communicate information from the source to the information receiver. Sonification is a subtype of auditory displays, and there have been many different definitions of how to exactly define a sound classified as a sonification. The first definition from the *Sonification Report* stated that "Sonification is the use of non-speech audio to convey information". [26] This definition clearly excludes speech from the sounds being classified as sonification, which was a main priority at the time[2]. However, this definition excludes neither real-world interaction sounds nor

[1]The terms “data” and “information” are used more or less interchangeably here in a manner consistent with Hermann’s definition of sonification [39]. For other perspectives, see for example [12], which includes a thorough epistemological discussion of the term "information" and how it can be transmitted through sound.

[2]Now been disputed, see [38] and [12].

music. Therefore, another, more detailed definition is also given in the *Sonification Report*, stating that

> "Sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation",

in which the focus is on the transformation from data to sound. As Hermann argues, the word transformation has been used interchangeably with "mapping", i.e. "mapping" data relations to sound parameters. [39] He further argues that this was adequate when parameter-mapping sonifications (see below) were dominating. However, with the introduction of model based sonifications (see below), where the relation between the sound and the data is not as straightforward as simply "mapping" data to sound, Hermann stresses the need for another definition which incorporates this complexity of data-sound relations.

Hermann also points to another reason why another definition was required: sonification was at the time being used more and more in arts and music. Sonification can definitely be a technique an artist might want to exploit in a piece of music, and sonifications might also sound musical, and music might sound like sonification, but they are not the same. Hermann therefore stresses the need to systematically define sonification as a scientific principle.

Consequently, Hermann develops four necessary and sufficient conditions for a sound to be classified as a "sonification". These are as follows:

1. The sound reflects *objective* properties or relations in the input data.
2. The transformation is *systematic*. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change.
3. The sonification is *reproducible*: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.
4. The system can intentionally be used with *different data*, and also be used in repetition with the same data.

3.2 Taxonomy of Sonification

As stated in the *Sonification Report*[26], a discussion of the theory of sonification should, among other things, include taxonomic descriptions of sonification techniques based on psychological principles or display applications. Such descriptions can be achieved in several ways, but usually categories emerge from either the function of the sonification, the sonification approach, or perhaps the most

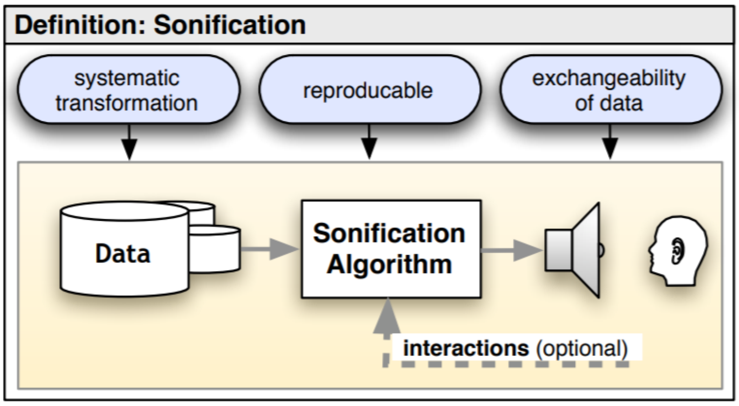

Figure 3.1: Illustration of the definition of sonification proposed by Hermann, extracted from [39].

commonly used, the sonification technique. All these views provide valuable insights to understanding different types of sonifications, and will be discussed in turn now.

3.2.1 Functions of Sonification

Seeing that the purpose of a sonification is to mediate information, it is natural to categorise the purpose, or function, of the communication of information. The functions of auditory displays have traditionally been defined in terms of three categories:

1. alarms, alerts, and warnings;
2. status, process, and monitoring messages;
3. data exploration. [45]

In [47], Walker and Nees added a fourth category:

4. art, entertainment, sports, and exercise.

Alerting functions

This refers to sounds that indicate the occurrence of a particular happening, either as a notification, an alarm, or a warning. The message conveyed usually convey a very limited amount of information, although the information content vary depending on the nature of the notification, alarm, or warning signal.

Status and progress indicating functions

In scenarios where more detailed information of a system is required, the sonification need to express the ongoing status of the system in real-time. In such cases, the ability of the auditory system to detect small changes over time is taken advantage of. Such sonifications are especially useful in monitoring situations where the user needs to free their sight for some other task.

Data exploration functions

Sonification for data exploration functions include auditory displays designed to facilitate data exploration, and focus on conveying information about conveying a more holistic picture of the data in the system rather than condensing information to capture momentary states.

Entertainment, sport, and leisure

This class include auditory interfaces that have been designed for use in exhibitions or for leisure and fitness activities. In many instances, the goal of this has been accessibility in sports and games. However, this class also include sonifications used in art installations and musical compositions.

3.2.2 Sonification Approaches

Another way to organise and define sonification is to describe them according to their sonification approach. In [8] De Campo categorizes sonification methods based on three data representation approaches:

Discrete Point Data Representation

In discrete point data representation, individual events are created for each data point.

Discrete point data representations provide more flexibility and feeling control over the data.

Continuous Data Representation

In a continuous data representation, the data is treated as quasi-analog continuous signals.

Continuous data representations provide advantages such as subjective perceptual smoothness and good representation of structures changing rapidly in time.

Model-Based Data Representation

Employs a more complex mediation between sound and data, by a model whose properties are informed by the data (also see Model-Based Sonification below).

De Campo then proposes a sonification Design Map, a continuum on which he places these three categories.

3.2.3 Sonification Techniques

The function or the approach of a sonification are important features that allow for intuitive categorizations. However, the most common way of defining different types of sonification has been to define them in terms of technique, or method, describing how the linkage between the data and sound is realised. The five categories of sonification[3] that are usually differed between, with the addition of one recently defined new category, will be discussed in turn now.

Auditory Icons and Earcons

Auditory icons are short moments of non-speech sound that aim to represent an icon in a way that is intuitive to its meaning in the user interface. A commonly cited example is the sound made when emptying the trash can on an Apple Computer: the sound this operation makes is that of paper being crumpled up and thrown away. In this case the action directly relates to the auditory experience, which is the essence of what an auditory icon is. [5]

Auditory icons can also be parameterized, which entails changing loudness, playback rate, or other sound parameters to express some physical quality the auditory icon is representing, for example size or energy. [5]

Earcons are very similar to auditory icons, with the difference being that there is no immediate link between the sound output and the operation it is representing. The relationship between sound output and the data it is representing needs to be learnt. [31] An example of an earcon is the sound a notification makes on a mobile phone device.

Audification

In audification, the relation between data and sound is very intimate: the sequence of data is directly mapped into sound pressure levels. It is in a way a direct alter-

[3]It is worth to mention that sometimes, especially before the more recent formal definitions of sonification, the term sonification is used only to describe parameter mapping sonification and other techniques sonifying complex data, whereas auditory icons and earcons are distinguished as separate, sometimes also separating sonification and audification. However, with Hermann's formal definition in [39], all these different techniques fit the description. Following Hermann's argument that there is no reason why sonification cannot be defined as sonifying single data points, there is no reason for distinguishing auditory icons and earcons from other sonification techniques.

native approach to visualisation where a data waveform is visualised by drawing a graph. Different signal processing techniques can be utilised to alter the sound or focus on certain aspects of the data and can be very effective at this, but is not as versatile as other techniques. [14]

Parameter-Mapping Sonification

In parameter-mapping sonification (PMSon), the link between data and sound is more abstract: features of the data are used as input for mapping functions, which in turn compute synthesis parameters for some kind of sound synthesis. The range of different synthesis methods and exact mappings that can be realized makes this a flexible method of sonification. [16]

As pointed out in [34], PMSon is arguably the most commonly used sonification technique. Appendix A contains further theory on this sonification method, as well as the derivation of notation that will be used later on.

Model-Based Sonification

Model-based sonification (MBS) data/sound linkage is realised by turning the data into a sound-capable system, which will produce sound when interacted with by a user. MBS is therefore intrinsically interactive. A typical example of MBS is that the data parameterizes some system, for example a mass-spring system, that is in a state of equilibrium (silent), until acted upon by a user. [37]

MBS is the last of the five established types of different sonification techniques[4] However, the list of techniques is not yet exhaustive, and new ideas, functions, and other developments might call for definitions of further techniques. Which technique to use, should be influenced by the type of data one aims to sonify and what the aim of the sonification is.

3.2.4 The convergence of taxonomies of function and technique

Looking at the sonification functions, approaches, and techniques, it is clear to see that they are related. Sometimes the function also indicates the technique, for example it is not difficult to see how the natural choice of technique when wanting an alerting function is auditory icons or earcons, whereas the choice of

[4] Another technique that recently(2018) has been defined, is Wave Space Sonification (WSS). In this method, the sonification process is realised by moving along a data-driven trajectory in some scalar field, defined in terms of mathematical functions or pre-defined samples. There are not many implementations of this method yet, but because of the nature of the mapping process, which can easily deal with an unlimited number of dimensions, it seems particularly promising for high-dimensional data. [40]. However, there is currently no more implementations or evaluations than in Hermann's original paper

technique when the purpose is data exploration for example can be MBS. Similarly, event-based approaches are the only ones used for alerts, notifications, and alarms. So function, approach and technique are intrinsically intertwined, and sometimes hard to distinguish between.

3.3 Limitations: The Problem of Perceptual Subjectivity

Lastly, a mention of subjectivity is appropriate. As established, sonification is by definition an accurate scientific method which leads to reproducible results. However, similar to other techniques that acts as the bridge between data and the human sensory system, subjectivity in human interpretation is inevitable.

Factors that will affect interpretation of sonification include individual musical abilities and taste, perceptual capabilities, cognitive abilities, and familiarity with auditory interfaces, although currently there is a lack of research done on exactly how these aspects affect judgment. [47]

3.4 Interaction in Sonification

Many types of sonification do not involve any type of user interaction. At the time when sonification was being established as a field of interest, all sonification was by default non-interactive because of the computing power needed to generate the sound output. The technology to manipulate the data or the sound in a real-time setting was simply not there. [22] However, today the picture is completely different, making interactive sonification an interesting area

In 2004, the Interactive Sonification workshop was organised for the first time, and has since been organised every third year. The proceedings of these workshops constitute much of the work done in the field of Interactive Sonification. In a paper from the first workshop, Hermann and Hunt defined Interactive Sonification as follows:

Interactive Sonification is the discipline of data exploration by interactively manipulating the data's transformation into sound [18]

Interactive Sonification therefore concerns the sound-producing interaction between a user and an auditory interface. In particular, it raises questions about how humans interact with sounds in real life, and how to utilise this relationship in order to communicate information intuitively in an auditory interface.

3.4.1 Auditory Perception-Action Loop

Every time we interact with a physical object, a sound is produced. And from this sound, we can deduce a lot of information. Firstly, it confirms our contact with the object- we can feel and see the contact, but we can also hear it. We can also deduce various properties of the material- whether it is hollow or solid, soft or hard, etc. As we move the object around, the sound is constantly providing us with feedback about its state. Sound is a temporal indicator of the physical processes that are happening around us. [22]

There are many ways of introducing elements of these natural perception-action loops in sonification. The user can manipulate the sonification mappings, or the data itself, to produce a sound output. Certain sounds can be used to signify user interactions, such as the accomplishment of a task, or reaching a certain point. The possibilities of utilising the relationship between sound and action are endless, but the fundamental idea is that

3.4.2 Formulation of Final Problem Statement

The advantages and disadvantages of a continuous and discrete sonification approach were briefly discussed previously in this chapter. However, this has not been extensively explored for interactive sonification. What will work better in an interactive sonification setting, when the user is in a tightly coupled auditory control loop? Is it better with continuous sound feedback that will change when acted upon by a user, or a discretized sound feedback that will fade out when not the user is not interacting with the sonification?

The final problem is formulated as follows:

In a multimodal interactive science simulation, does a discrete or continuous data sonification benefit the user experience?

Chapter 4

Design

This chapter will describe the design of the sonification for the wave-interference PhET simulation. Any interactive science simulation contain an underlying model that is based on some scientific principles and mathematical equations, and that allow the user to change some model parameters and instantly experience the outcome of those changes. [13] It follows that any sonification that is added to the simulation should express aspects of this model, and the design of the sonification is therefore directly dependent on the model and its parameters. Consequently, the chapter begins with outlining the model of the wave-interference PhET simulation, before proposing design methods to represent this model with sound.

4.1 Wave Interference Simulation

The wave interference was chosen because it is a versatile and interesting simulation, where the simpler modes allow for easy sonification prototyping, that can easily be extended to the whole simulation later. It is particularly interesting for investigating discrete and continuous sonifications because it consists of both continuous and discrete phenomena. It also does not so far have a sonification by the PhET development team. Furthermore, it is aimed for a very broad age group, and is listed under all grade levels, i.e. elementary school, middle school, high school and university, on the PhET website, which is convenient for testing purposes.

The wave interference simulation is a physics simulation that aims to teach students about wave behaviour. There are three different options for the wave source: a dripping faucet, an audio speaker, and a laser. The user can choose between three different scenarios/screens, one in which there is one single wave source, one where there are two wave sources to show interference, and one where slits are introduced to show wave diffraction.

The first scenario, the "waves screen", depicts a 2-dimensional spherical wave, either on the surface of water, or a sound or light wave. The user can interact with the waves by controlling the frequency and the amplitude, and observe what happens. The waves obey the relationship

$$v = f\lambda \tag{4.1}$$

where v is wave speed, f is frequency, and λ is wavelength.

The second scenario, the "interference screen", consists of two in-phase, spherical point sources that can be enabled and disabled independently, and interference patterns emerge from the overlap of the waves. The interference pattern shows constructive interference at

$$dsin(\theta) = m\lambda \tag{4.2}$$

where d is the distance between the centre of the wave sources, $sin(\theta)$ is the angle, m is the .., and λ is the wavelength.

Thirdly, the "slits screen" consists of an incoming plane wave (as opposed to the spherical waves before), where the user can control the location of the barrier, the number of slits (double or single slit) and the placement and width of the slits. The minima and maxima respectively can be found at

$$asin(\theta) = m\lambda \tag{4.3}$$

$$asin(\theta) = \frac{m+1}{2}\lambda \tag{4.4}$$

, for single slit, where a is the width of the aperture, and

$$dsin(\theta) = \frac{m+1}{2} \tag{4.5}$$

$$dsin(\theta) = m\lambda \tag{4.6}$$

, for double slit, where d is the distance between the centres of the slits.

4.2 Designing Sonifications for the Wave Interference Simulation

It was decided to begin with the waves screen only, as this is the basis that all the screens are built upon, so it can easily be extended to the other screens later.

The learning goal of the simulation is to present various wave characteristics. For the waves screen, these characteristics are mainly the wave frequency and amplitude, and how this changes the propagation of the wave, and how this compares for different wave media. The sonification should therefore communicate frequency and amplitude characteristics. Moreover, to facilitate a complete auditory perception-action loop, every user action in the simulation should have an auditory response. This means that every button the user presses on the screen should have a different sound attached to it.

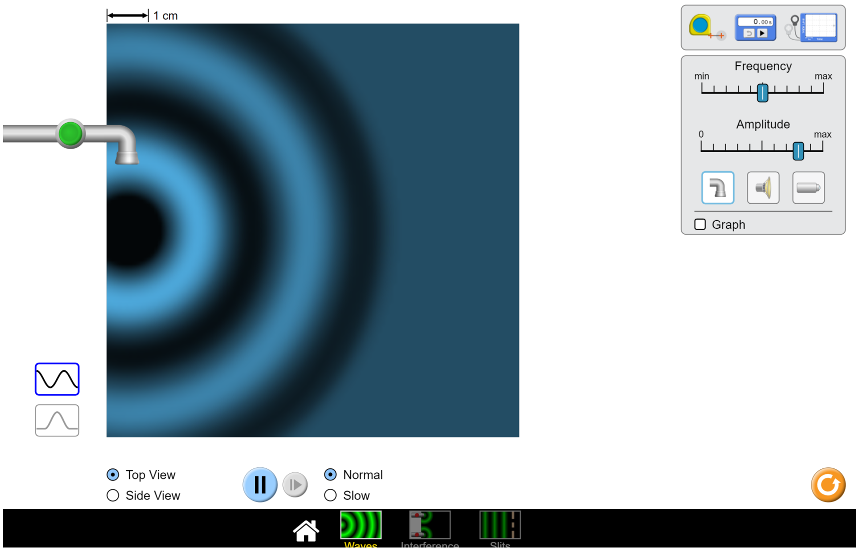

Figure 4.1: Screenshot from the waves screen for the wave-interference simulation.

The problem statement is to investigate a continuous sonification vs. a discrete, or event-based sonification. Therefore, two different designs are needed, one in which the user takes part of and changes a continuous sound stream, and one with discrete sound events, where every user interaction is sound producing, but for a limited time. Important in both of these designs is that every user action should immediately be followed by a sound outcome, to imitate the perception-action loop from real life sounds.

Because the two parameters that can be changes by the user is amplitude and frequency, it is natural that any sonification, whether discrete or continuous, expresses these two properties.

An important point to take into consideration is consistency across the different screens within the same sonification scenario. Because of the different natures of the wave sources, it could be tempting to make dramatically different sonifications for each of them. However, the simulation is trying to communicate the same phenomena but through different means, and this should be respected. This means that the sound output of changing one parameter in one scene should be congruent to the sound output of changing that parameter in another scene. Nevertheless, since each scene has slightly different qualities as well as parameter ranges, each of the screens, both for the discrete and the continuous scenario, will be discussed separately.

4.2.1 Discrete Sonification

The main purpose of the discrete sonification is to provide the user with a sound that changes according to how the amplitude and frequency is changed by the user, but only in the moment the user is changing the parameters. This means that any change will be sound producing, but when not acted upon by the user, the sounds will fade out.

Water Scene

It seems natural to map the frequency of the wave to the playback rate of the sound, and the wave amplitude to sound amplitude. Loudness is not always recommended as a sound parameter in sonification [16], but because amplitude here also is a variable in the data, where zero amplitude corresponds to no sound, this suggestions does not seem applicable.

From real-world interactions and physical laws, it is expected that when putting more energy into a system, it will also be active for a longer period of time (e.g. with a vibrating string, throwing a rock, rolling a ball, anything where energy is involved). Because amplitude and frequency are both related to the energy of the system, it is natural to represent this relationship in the sonification. This will be realised by altering the delay time of the sounds. Whereas frequency is directly proportional to energy, energy is proportional to squared amplitude. This should be taken into account with the delay times.

In addition to changing the amplitude and the frequency in the water scene screen, a natural event to sonify in the discrete sonification is the water drop hitting the surface. A sound sample should be played every time a drop hits the surface. Because perfectly repeated sounds are very unnatural and also can be very tiring [22], there should be a small collection of sounds that are randomly picked from every time the drop hits the surface. From real life interactions, it is expected that a bigger drop sounds not only louder, but "heavier". This has to do with the pitch changing as the size changes. This can be accounted for by changing the pitch of the water drop sound as the amplitude changes.

Sound Scene

Again, in the sound scene, it is natural to map amplitude and frequency as in the water scene. Since the frequency range of this is within the audible range, it is natural to directly map the frequency in the simulation to the frequency of the sound output.

The same relationship between energy, amplitude and frequency is true for sound waves, so it is natural to adopt the delay time mapping described for the water scene.

Light Scene

For the light scene as well, the amplitude and frequency of the light wave will be mapped to sound loudness and playback rate of the corresponding sound. The relationship between energy and delay time will also be the same.

4.2.2 Continuous Sonification

In the continuous sonification, the sound output will begin when the user turn the wave source on, and there will be a constant sound output until the user turns the wave source off again. By changing the amplitude and frequency parameter, the user will alter the sound constant sound stream accordingly.

4.2.3 Water Scene

For the water scene, a sound will start to play then the first water drop hits the surface of the water, and the playback rate will change according to the wave frequency, whilst the sound loudness will be mapped to the wave amplitude, similar to the discrete case.

A low frequency oscillator will be used to perform amplitude modulation on the sound output, in accordance with the wave frequency.

4.2.4 Sound Scene

Since the frequency range in the sound scene naturally is within the audible range, it is natural to use the method of audification to sonify this data, i.e. simply create an oscillator that oscillates at that changes frequency as the interacts with the frequency slider. Similarly to the other cases, the sound loudness will be mapped to sound amplitude.

4.2.5 Light Scene

Once again, in the light scene, a continuously looping sound in turned on as the light is turned one. Changing the light amplitude and frequency will change the amplitude and frequency of the sound stream.

To summarise the continuous sonification scenario: turning on the wave source in each of the screens turns on a continuous sound stream, whose playback rate and loudness is controlled by the user's interaction with the frequency and amplitude slider, scaled to appropriate values for each of the screen's ranges. Additionally for the water screen, there is an LFO whose frequency is mapped to the wave frequency.

4.3 Other Sounds

In addition to the model-related parameters, there are several buttons the user can push to navigate the simulation. Because the aim was to create a simulation that is a complete sound producing system, interacting with these buttons should also be a sound producing action. To achieve this, earcons were added to these actions. The relevant actions include:

- Turning source on/off
- Play/pausing the simulation
- Reset simulation
- Switching between screens

Turning source on and off correspond to pushing the same button on the screen, but should have different sound outcomes. The same is true for playing and pausing the simulation.

Chapter 5

Implementation

This chapter will describe the implementation of the two sonification scenarios described in chapter 4. Firstly, it will briefly describe how the framework of the PhET simulation code, and how the wave-interference simulation is organised, and a few simplifications that was made to the simulation code. Then the sonification algorithms and sound producing code will be explained.

5.1 PhET Specifications and Tools

The Wave Interference simulation (and all other up-to-date PhET simulations) is implemented in JavaScript ECMAScript 6, with RequireJS[1] used to support modularization of the code. This means that each JavaScript script is treated as a RequireJS module, and code from independent scripts can be accessed by calling the require function.

Another key feature of the PhET simulation development is the model-view controller (MVC) design pattern. MVC divides the program into three interconnected elements, i.e. the model, the view, and the controller. The model is the core component of the pattern, and in the model lies all data and information the program contains. In the view, all this information is presented, whereas the controller accepts user input and converts it to commands for the model or the view.

The wave interference simulation is also organised according to this. There is one folder for each of the screens, and one folder for common elements. The "common" folder contains all the model for the three different wave types. There is one WaterScene, one SoundScene, and one LightScene script. Each of these contains the specific features for the different wave types, and calls scene specific classes such as WaterDrop and SoundParticles.

For each of the screen folders there is one folder containing "view"-scripts, and one folder containing "model"-scripts. The model scripts contains all the informa-

[1]https://requirejs.org/

tion about the wave behaviour, i.e. the equations described in 4. Any sonification would then also be placed in the view, as it presents information from the model.

As mentioned, some of the PhET simulations are already sonified. To support the sonification of the simulations, a library containing sound generators also exists within the PhET framework, called "tambo". This library contains valuable resources for sonifying the simulations, with sound generators that can be extended and customized for specific purposes. It allows for the creation of various sound generators without having to code everything from scratch.

5.1.1 Adapting and Simplifying the Simulation

To facilitate the development of sonification scripts, a new simulation was created from the template sim, following the steps for creating a new sim described in the PhET Development Overview [2]. Then relevant modules were copied from the source code for the Wave Interference sim. Several features from the original simulation were omitted from this implementation, because they were not seen as necessary for the purpose of this thesis. Moreover, some features were seen as potential disturbances that would compete for the attention of the user, and steal attention from the sounds.

[2] https://docs.google.com/document/d/1Ys1EiwnqQGYuzGOcQSr4uXDes35mF1v1XhMZIl10nk8/

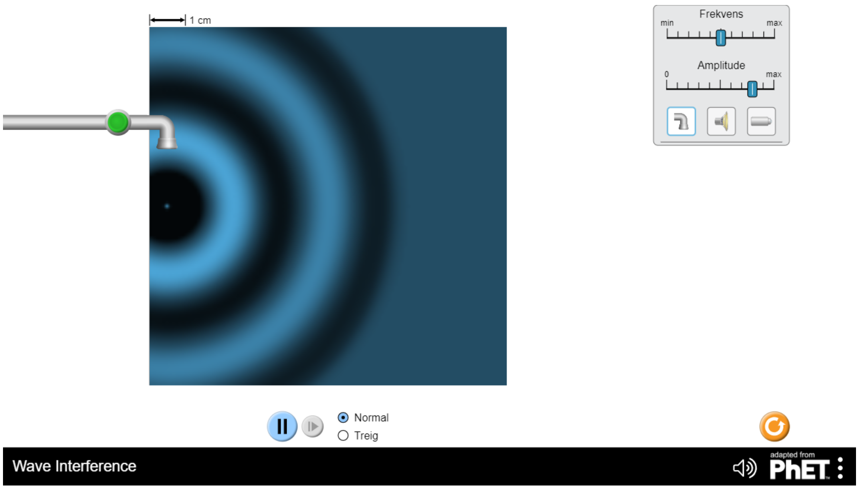

Figure 5.1: Screenshot from the waves screen for the altered wave-interference simulation. Compared to figure 4.1, it is clear that many features have been removed to simplify the simulation. The variable names on the screen have also been translated into Norwegian.

5.2 Discrete/Event-Based Sonification

The discrete sonification implementation consists of sound generators for the amplitude and frequency property in each of the screen views. As discussed in 4, the wave amplitude is mapped to the loudness of the sound sample played, and the wave frequency is mapped to the playback rate. The ranges are normalised, and the the values are put into bins.

For the water view, every time a water drop hits the surface of the water, a sound is played. The amplitude of the sound is mapped to the playback rate. To create some sound variation, three different sound samples are picked from at random each time a sound is played.

5.3 Continuous Sonification

The continuous sonification implementation consists of a sine wave generator built from the Web Audio API OscillatorNode for the sound screen, and sound generators that play a looping sound when the wave source is turned on for the water and the light screen. As described in chapter 4, the playback rate is mapped to wave frequency, and the wave amplitude to the sound loudness, with appropriate normalizations of the ranges.

The framework described here is general and can work with any sounds. For a discussion of choice of sounds for the final design, look to chapter (aesthetics).

Chapter 6

Testing

Finding the best measure to test usability of a display is a demanding task, and testing sonification techniques in particular is not always straight-forward. Standard measures of usability have been applied to auditory interfaces, such as the SUS (System Usability Scale [23] and UMUX (The Usability Metric for User eXperience) [24]. However, the problem with blindly extending these measures to auditory interfaces is that they are not specifically aimed for the right purpose. As a result, they might be confusing and inappropriate for use with sound, and also might not capture crucial aspects of what an auditory interface should do. Another problem is that most people do not have a lot of experience with auditory interfaces, introducing the need for less general questions which do not allow for as much interpretation as in general user experience measures.

Therefore, for this project, a relatively recent framework called BUZZ has been chosen [41], which is specifically developed for auditory interfaces. The complete set of audio user experience statements in BUZZ is as follows:

1. The sounds were helpful.
2. The sounds were interesting.
3. The sounds were pleasant.
4. The sounds were easy to understand.
5. The sounds were relatable to their ideas.
6. It was easy to match these sounds to their meanings.
7. It was difficult to understand how the sounds changed from one variable to the next.
8. It was fun to listen to these sounds.

9. It was confusing to listen to these sounds.
10. It was easy to understand what each of the sounds represented [41].

These questions were adopted and used in the testing procedure. In addition, some other questions about the user experience of the simulation itself, and not only the sounds, were added. This was done to see if the user experience of the simulation was affected by the sonification scenario. The full set of questions from the final testing procedure, in both Norwegian and English, can be found in appendix C. Each of the questionnaire items were Likert scale items that could be answered on a scale from 1 to 7.

6.0.1 Pilot testing

To validate experimental procedures, a pilot-test was conducted prior to the experiment. Three participants took part of the pilot test. From observations during the experiment, it was clear that some questions were phrased a bit difficultly, and that the first part of the questionnaire contained too many questions. By the time of the second questionnaire it was clear that the participants were tired. Some questions were simplified and some questions were removed, before continuing the test with the questionnaire as seen in appendix C3.

6.1 Testing procedure

The testing was conducted at Norsk Teknisk Museum, an interactive science museum in Oslo. Over the course of two days, 22 participants, 14 female and 8 male, aged 13-26, took part in the experiment. The experiment set-up was located at the beginning of the museum's own exhibition, but separate from the other installations. School students and other museum guests were asked if they wanted to take part in a listening experiment.

The participants were all given the same description of the experiment; merely that it was an experiment consisting of one application with two different sound setting, and that they would be asked a few questions about each of these. Any further description of the purpose of the experiment or sonification was avoided to avoid any biases that could introduce. Then they were asked to play freely with the simulation. A few participants needed some slight guiding, for example to push the source on/off button, and to switch between the screens. As a final note, the participants were also instructed (as deemed appropriate as many of them were school students, and it was during the school day), that there were absolutely no right or wrong answers, but that the experiment was only to record their subjective opinions and preferences in reaction to the stimuli.

The test was set up as follows: the participant would be introduced to the simulation with one of the sonification scenarios. After playing with this for as long as they wanted, they would complete the first questionnaire. Then the participant would be introduced to the simulation with the second sonification scenario, play around with this, then complete the same questionnaire as before. The last part of the survey then asked which scenario the participant preferred, and the reason why, before having the option to add a comment.

As an attempt at eliminating any learning biases resulting from an increasing familiarity with the simulation, every other participant started with the discrete sonification scenario.

Each test took around ten minutes, including test introduction, play-time, and questionnaire-time. However, this varied a lot, and especially the younger audience chose to spend more time exploring the simulation.

Chapter 7

Results

This chapter presents the results from the experiment outlined in chapter 6. It separates the results in two categories: quantitative and qualitative.

7.0.1 Quantitative Results

The quantitative results are the questions that are in Likert-scale form.

The questions are grouped into category. (aesthetics, usability, immersion, etc.)

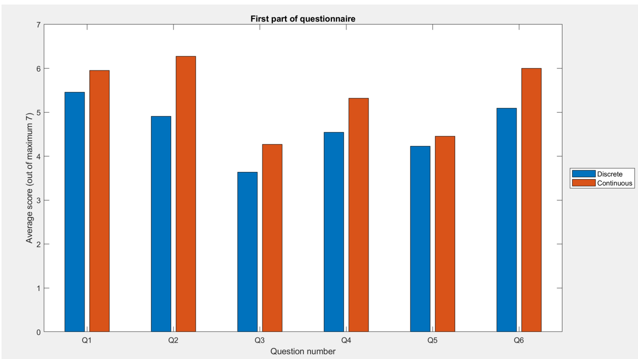

Figure 7.1: The average ratings for the first part of the test, regardless which scenario the participant was given to begin with.

Extracting only the results from the group of participants that were first introduced to the discrete sonification scenario:

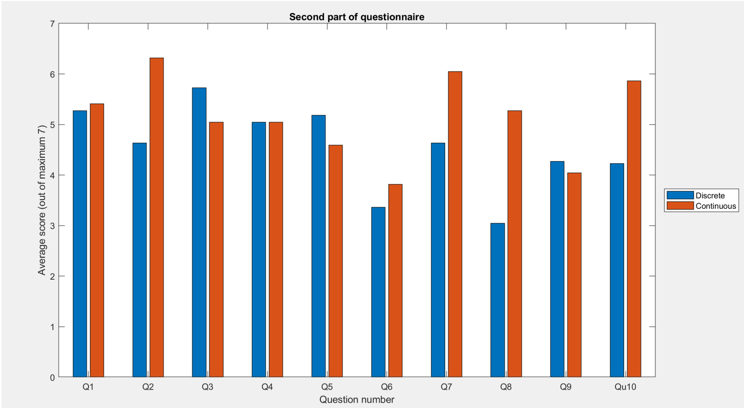

Figure 7.2: The average ratings for the second part of the test, regardless which scenario the participant was given to begin with.

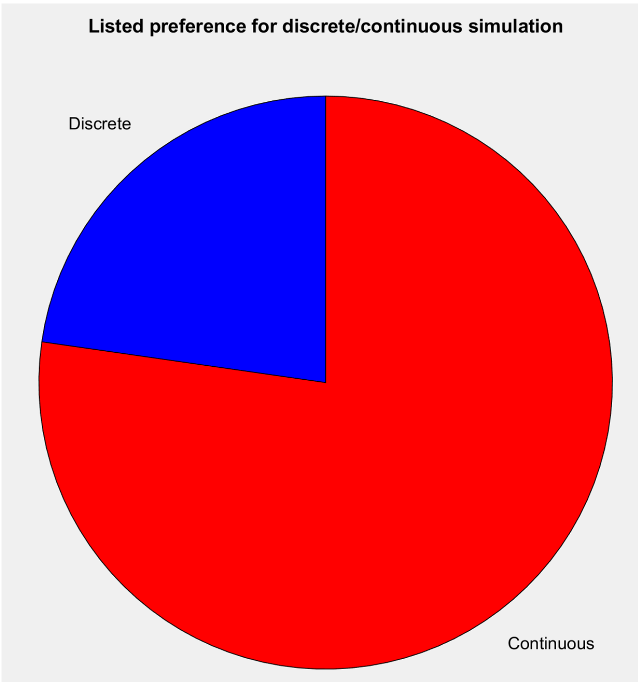

Figure 7.3: The results from the question where the participants were asked to state their preference between the two simulations.

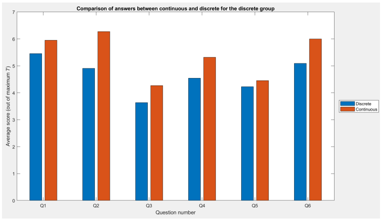

Figure 7.4: Average ratings for the first part of the questionnaire for the "discrete group"

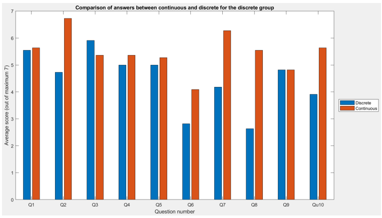

Figure 7.5: Average ratings for the second part of the questionnaire for the "discrete group"

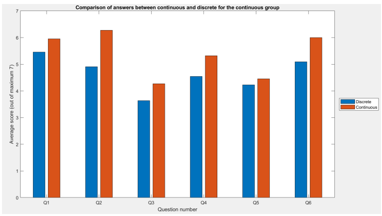

Figure 7.6: Average ratings for the first part of the questionnaire for the "continuous group"

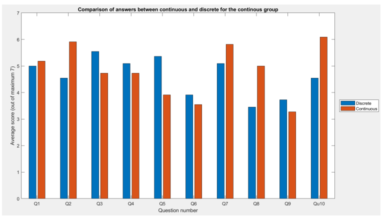

Figure 7.7: Average ratings for the second part of the questionnaire for the "continuous group"

7.0.2 Qualitative Results

The qualitative results are the additional comments on the questionnaire, observations made during the experiment, and conversations with the participants that were not a part of the questionnaire. Reactions and comments from the participants also provide valuable feedback.

Some of the comments from the participants (translated from Norwegian), included:

- "I did not notice that you could see the light waves in the first (continuous) one, was so focused on the sounds" (this participant also chose the discrete sonification over the continuous one in the question that concerned this)..
- "I preferred the one with the most sound, the other was boring"
- "The sounds in simulation 2 (continuous) made it easier to understand the amplitude, than just by colours."
- "Did not notice that you could see the sound waves in the first (continuous) one, was so distracted by the sounds."
- "The sounds made it easier to understand what was happening than in number one (discrete)"
- (preferred the continuous..) Because in this one I had more control over the sounds. I thought it was less disturbing without the "clicks"
- "The second one (discrete) was very boring compared to the first one. I thought that it was easier to understand what was changing when the sounds were constantly changing too. The other one was very uniform"
- "It (discrete) was a lot easier to understand, the other was a bit "messy""

The original replies in Norwegian, included the ones not listed here, can be found in appendix D

From observation, the continuous scenario also seemed to invoke more physical reactions, i.e. facial expression such as smiling, surprise or confusion.

Chapter 8

Discussion

This chapter will review the results that were presented in chapter 7. Once again, the qualitative and quantitative results are treated separately.

8.1 Quantitative Results

By quickly glancing at the results for the discrete and continuous sonification scenario, it seems that the continuous scenario quite consistently scores slightly higher than the discrete scenario. This is also confirmed by calculating the overall scores of the usability test.

However, performing a two-sided Wilcoxon rank sum test between the results for the discrete vs the continuous scenario, reveals a p-value of 0.175. This is a very high p-value and means that the null hypothesis cannot be rejected. Whereas this does not mean that there is no significant difference between the two sonifications, it means that the obtained results alone cannot establish a statistically significant difference in measure user experience.

Despite of this, there clearly is a preference for the continuous sonification scenario, which the results from the preference question (see figure 7.3). The reason for this preference can not be found in user experience results, but the results from the qualitative answers can shed more light on this.

8.2 Qualitative Results

More than three quarters of the participants stated that they preferred the continuous sonification scenario. Many of the justifications for this mention that the discrete one was boring and more uniform compared to the continuous one, and the continuous one was a lot more fun and had nice sounds. In conversations with the participants, they also often mentioned that they thought the continuous sonification scenario was fun to interact with. The red thread in all of this seems to be that the continuous sonification scenario provided a more interesting, engaging, and overall fun experience.

Several participants also mentioned that they felt like they understood more from the continuous sonification scenario, and that they learnt more from it. However, these are very ambiguous comments, and might have been in accordance with the nature of the testing location and what they thought were expected of them, rather than a description in their own words. Nevertheless, it is hard to measure this without any systematic testing.

Despite of the overall preference for the continuous sonifications, it is also worth to mention the participants who preferred the discrete sonification scenario. One comment was particularly interesting: "I did not notice that you could see the light waves in the first (continuous) one, I was so focused on the sounds." This brings up a topic from the discussion of advantages and disadvantages of continuous sonification from **??**: that a continuous sonification can be overwhelming and overpowering. Another participant also mentioned that the continuous sonification scenario was a bit "messy", which also is related to this.

However, although some of these comments provide interesting insights, they cannot contribute towards answering the problem statement concerning usability. For this further testing is required.

Chapter 9

Conclusion

The aim of this thesis was to review relevant theory and research in order to create an interactive sonification for a multimodal physics simulation. An overview of sonification was given including historical context and account of sonification today. Some sonification theory was formalised, including definitions and techniques, before introducing the topic of interactive sonification and the idea of auditory action-perception loops.

The specific research goal of the thesis was to investigate whether a discrete or continuous sonification would improve user experience the most. Two different sonification scenarios for the wave-interference PhET physics simulation were designed and implemented, with the design process also involving a short test of different sounds with respect to sonification aesthetics. With the final design ready, an experiment aimed to measure user experience for the two scenarios was created. The experiment was carried out at an interactive science museum, with 22 participants.

There was a measured preference for the continuous sonification scenario, both from the test itself, and from observations made during the experiment and conversations with the participants. However, with the current results, there is no statistically significant difference in usability ratings for the two scenarios, and more testing and/or a revised testing procedure is required to give a conclusion to this.

Chapter 10

Reflections, limitations, and thoughts about future work

One possible limitation in the testing procedure was that the three different screens were treated the same. However, the different nature of water and the two other scenes means that the the ratings for one sonification scenario might not be the same for all three screens. However, with the current test, there is no way of differing between these.

The testing procedure described here exclusively deals with user experience, which is and should be an important part of an educational simulation. However, as mentioned in section 2.2, one of the purposes of sonification is adding another method of interpretation to deepen the understanding of the data/model. This was not tested in this project, although some of the qualitative answers mentioned that the participants felt that they understood more in the continuous sonification view. It would be interesting to test this further by conducting an extended experiment with a focus group with the intention of systematically evaluating the learning experience.

For the purpose of keeping the problem statement as isolated as possible from other factors, the sonifications were relatively simple so that the only difference in the two scenarios would be whether it was discrete or continuous (with some obvious exceptions). There is therefore many possibilities for adding more parameters to the mappings, making the sonification more complex.

Lastly, the sonifications should be extended to all the screens. The sound now only works in a limited part of the full simulation, but this could be easily extended and modified to make the whole simulation sound producing.

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Appendix A

Parameter Mapping Sonification

This section will expand on the theory of parameter-mapping sonification given in chapter 3, for the purpose of systematically introducing the mapping notation used in 4. It is placed in an appendix because it is not seen as strictly necessary to understand PMSon or the notation used in the thesis, it provides valuable insights to any ready who wants a more formal definition of the topic.

Connecting Data and Sound

Exactly how the data features are connected to the sound synthesis parameters is described by the *mapping function*. The mapping function introduce two different issues to be solved: the first is how to describe the transfer function, i.e. the function which connect the data domain of hard facts to the perceptual domain of sound. The second issue is the mapping topology, i.e. how the data features and synthesis parameters are linked so that the resulting sound is perceptually valid.

The Transfer Function In his thesis, Hermann develops a mathematical framework of how to define the transfer function.

The formalisation begins by assuming a d-dimensional dataset $\{x_1, ...x_N\}$. An acoustic event in the sonification is described by a signal generation function $\mathbf{f} : \mathbb{R}^{m+1} \to \mathbb{R}$ which computes a q-channel sound signal (for stereo sonifications, q=2) $\mathbf{s}(t) = \mathbf{f}(\mathbf{p}, t)$, a function of time. $\mathbf{p}$ is an m-dimensional vector consisting of acoustic attributes which are parameters of the signal generator. A PMSon is then described by

$$\mathbf{s}(t) = \sum_{i=1}^{N} \mathbf{f}(\mathbf{g}(\mathbf{x}_i \mathbf{x}_i \mathbf{x}_{i\mathrm{x}_i}),t),(A.1)$$

where $\mathbf{g} : \mathbb{R}^d \to \mathbb{R}^m$ is the parameter mapping function.

Let $\mathbf{x} = (x_1, ..., x_d)^T$ be a single data point in the set. The simplest parameter mapping directly maps values of a single acoustic attribute p_i from a single data

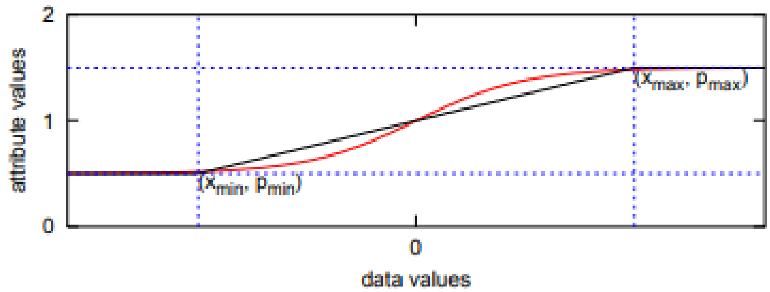

Figure A.1: The black line depicts the typical linear transfer function, whereas the red line outlines an alternative sigmoidal mapping. [38]

data feature		sound synthesis parameter
$\text{datafeature}_1[\_,\_]$	→	onset [10 ms, 20 ms]
$\text{datafeature}_2[\_,\_]$	→	freq [50 midinote, 52 midinote]
$\text{datafeature}_3[\_,\_]$	→	level [−18 dBV, 0 dBV]

Figure A.2: An example of the more textual mapping notation suggested by Hermann [38], figure extracted from [16].

variable x_j. This mapping can be described as

$$p_1 = h_1(x_{k1}) \tag{A.2}$$

$$p_2 = h_2(x_{k2}) \tag{A.3}$$

$$\ldots \tag{A.4}$$

$$p_m = h_m(x_{km}) \tag{A.5}$$

and its transfer function can be seen in figure no..

Hermann notes that this functional description formally describes PMSon and it suitable for its implementation, but suggests a less mathematical representation for describing mappings. In the notation Hermann suggests "_" means that mapping limits in the data domain are extracted from the smallest and greatest values from the data themselves. Instead of extreme data values, quantiles are often a good choice in order to make a sonification robust against outliers. n example of this notation can be seen in figure **A.2**.

Mapping Topology

The attributes in the acoustic domain are usually separated into signal-related parameters, such as the sound/signal onset, and perceptual-related attributes, such as sound level and frequency. Exactly how the data features are mapped to these acoustic attributes is known as the mapping topology.

One-to-one mapping One-to-one mappings are, as the name suggests, mapping where one data feature is mapped to one sound attribute, as depicted in the example in figure no.. An example of this is *Principle Component Mapping*, a method in which the information content of the data dimensions is quantified and mapped to sound parameters ordered by salience, so that the data channel with the most information is mapped to the most salient sound synthesis parameter. [38]

One-to-many mapping In one-to-many mappings, one data feature is mapped to two or more synthesis parameters, also known as divergent mapping. This means that changes in the data feature will lead to multiple changes in the sound characteristics. Overlapping ranges in the perceptual domain means that the output sound will be one single sound stream changing in multiple ways. However, by scaling the ranges in the perceptual domain, this method can be used when variations from small to large in the data must be highlighted.

Many-to-one mapping Many-to-one mapping, or convergent mapping, often is an indirect result of indedependent sound synthesis parameters, or for example when data features are mapped to physical modelling processes, and that a variation of two or more features mapped to this process seemingly change only one perceptual attribute.

Appendix B

Aesthetics Questionnaire

Appendix C

Questionnaire

This appendix contains the questions from the questionnaire. First is the original question in Norwegian that was used in the test, second, in italics, is the author's translation of them into English. Note that many of the questions were first translated from English to Norwegian as mentioned in chapter 6, but here the author's translation of them back into English is used, to stay true to their meaning in the test. Their meanings were slightly changed in Norwegian to fit the purpose and context of the testing, and are therefore slightly different to their English originals.

Preliminary questions about the participant's background:

1. Hvor gammel er du? *How old are you?*
2. Har du tidligere erfaring med "sonifikasjon"? *Do you have previous experience with "sonification"?*
3. Har du erfaring med å spille et musikalsk instrument? *Do you have any experience with playing a musical instrument?*

Question 1 was a short-answer text where the participant would put a number, the question 2 was a multiple choice question, with the options "Nei/*No*", "Ja, litt/*Yes, a bit*, and "Ja, mye/*Yes, a lot*, and the third question was also a multiple choice question with the option to answer nothing, 1-3 years, 3-5 years, 5-10 years, or 10+ years.

The first part of the test, about the simulation in general:

1. Jeg følte jeg hadde kontroll over hva som skjedde i simulasjonen *I felt in control of what was happening in the simulation*
2. Det var morsomt å bruke simulasjonen *Using the simulation was fun*
3. Det var vanskelig å forstå hva som skjedde i simulasjonen *It was difficult to understand what was happening in the simulation*

4. Simulasjonen var lærerik *The simulation was educational*
5. Det var vanskelig å forstå hvordan jeg kunne kontrollere hva som skjedde i simulasjonen *It was difficult to understand how I could affect what was happening in the simuation*
6. Simulasjonen reagerte umiddelbart på det jeg gjorde *The simulation reacted instantly instantly to my actions*

The second part of the test, about the sounds only:

1. Lydene var nyttige *The sounds were useful*
2. Lydene var interessante *The sounds were interesting*
3. Lydene var behagelige å høre på *The sounds were pleasant*
4. Lydene var lette å forstå *The sounds were easy to understand*
5. Lydene var relaterbare til ideene de representerte *The sounds were relatable to their ideas*
6. Det var lett å finne ut hva lydene betydde *It was easy to understand what the sounds represented*
7. Det var vanskelig å forstå hvordan lydene endret seg *It was difficult to understand how the sounds were changing*
8. Det var morsomt å høre på lydene *It was fun to listen to the sounds*
9. Det var kjedelig å høre på diffe lydene *It was boring t listen to the sounds*
10. Lydene var forvirrende å høre på *The sounds were confusing to listen to*
11. Da jeg hørte på lydene, blokkerte jeg alle andre lyder rundt meg *I blocked out things around me when listening to the sounds*

The questions in both the first and the second part of the test were Likert-style questions that could be answered on a scale from 1-7, where 1 corresponded to the lowest ranking, and 7 to the highest.

There were some post-questionnaire questions as well, concerning the participant's preference among the two simulations, the reason why, and the options to add any further comments.

1. Hvilken simulasjon likte du best? *What simulation*[1] *did you prefer?*

[1]The word "simulation" was used here instead of "sounds" or "sonification", even though strictly speaking it was the same simulation, to avoid confusion. The word simulation was also used to describe the experiment to the participants, deliberately saying simulation 1, simulation 2, etc.

2. Hvorfor likte du denne best? *Why did you prefer this over the other?*

3. Har du noen andre kommentarer? *Any other comments?*

The first question was a multiple choice question where the participant could choose between simulation 1 and simulation 2 (or, as with any of the other questions, leave blank), whereas the two last questions were long-answer questions where the participant could write what they wanted.

Appendix D

List of Qualitative Answers

These are the original answers (in Norwegian) to the last question of the test: "Why did you prefer this simulation?" (see appendix C for the full questionnaire.

- "nei"
- "likte best den med mer lyd, den andre var mye kjedeligere"
- "Lydene i simulasjon 2 gjorde det enklere å forstå amplituden, enn kun ved farger."
- "La ikke merke til at man kunne se lydbølgene i den første, ble så opptatt av lydene."
- "lydene gjorde sånn at det var lettere å forstå hva som skjedde enn i nummer"
- "Fordi her hadde jeg større kontroll på lydene. Jeg syntes det var mindre forstyrrende uten "klikkene""
- "forsto bedre hva som skjedde i andre simulasjon, mye gøyere"
- "Jeg kunne ikke høre noe på simulasjon 2"
- "mye morsommere, følte jeg forsto mer"
- "Den var mye morsommere"
- "lærte mer av den, veldig morsom"
- "forsto mye mer i denne"
- "veldig fine lyder"

- "Den andre var veldig kjedelig i forhold til den første. Jeg følte man skjønte mer hva som endret seg når lyden endret seg hele tiden. Den andre var veldig lik"
- "Den var gøyere, følte jeg lærte mer."
- "Den var mye lettere å forstå, den andre var litt "rotete""

Note that although there were 22 participants, there are not 22 answers to this question. This is because this last question was optional, and not filled in by everyone.