Interaction with sound for participatory systems and data sonification

Liu, D.

CHAPTER 7

Conclusions and Discussion

The research presented in this thesis is driven by personal curiosity as main motivation. The aim is to enhance the understanding of the chosen topics (i.e., interaction models, data sonification: interaction & design, evaluation of data sonification). Additionally, the research seeks to contribute new findings and perspectives to these areas of study.

We presented a narrative in Chapter 1, which revolves around the connections between sound and data, based on the three elements of the dialogue model (cf. Figure 1.2). In this chapter, we build upon this narrative and complement it by integrating the main results from previous chapters and aligning them with the corresponding research questions (see Figure 7.1).

It begins by exploring the current state of audience participation in scenarios where sound is controlled by or mapped to other forms of data. Through our investigation, we uncovered an essential relationship between learning and interaction, which led us to propose an ideal framework as the foundation for our subsequent research (see Chapter 2). Based on the insights gained from earlier findings, we proceeded to implement and experiment with various approaches to interactive sonification design (see Chapter 3 & 4). Our analysis and evaluation encompassed both interaction design and sonification design, considering the three elements of the dialogue model (see Chapter 3 & 5 & 6). Ultimately in this chapter, we delve into the discussion of potential directions for future research and development.

7.1 Conclusions

In **Chapter 1**, we introduced the topics covered in this thesis and established connections between them. One of the primary objectives of this thesis is to explore the interactive experience with sound and data. We utilized the dialogue model to define the interactive process and divided it into three components: subject, verbal and adjective (see Figure 1.1). ***While the subject represents the entity or role that initiates the dialogue, the verbal element enables subject input and actions. The adjective provides descriptive information on how the system responds to the subject's actions, particularly in terms of sound production.*** Through an expert analysis of the participants and the usage of sound interaction, we proposed an ideal interaction framework, which was then employed in the interaction and design of data sonification. In

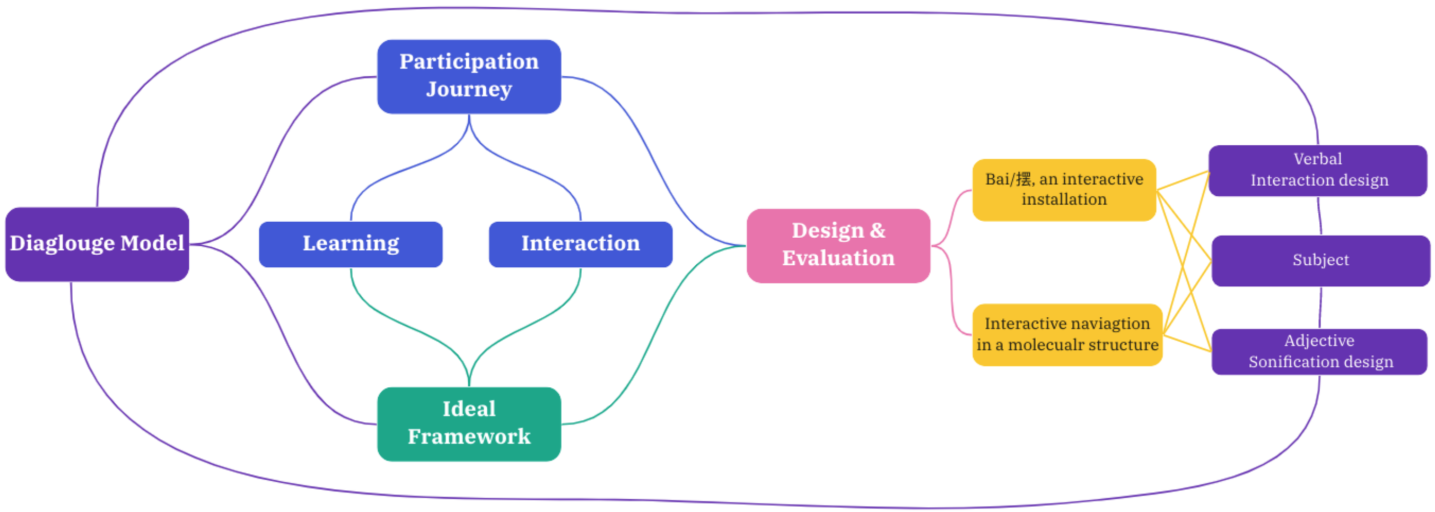

Figure 7.1: Dissertation narrative and structure. The figure presents a condensed outline that integrates the main findings from previous chapters and aligns them with the corresponding research questions.

the latter portion of our work, we explained the design and implementation of user evaluation techniques to evaluate the sonification designs.

7.1.1 Framework for Participatory Sound Interaction

In **Chapter 2**, we reviewed a series of real-time participatory musical performances and analyzed the dialogues between the audience and the systems in such interaction, in order to answer the first research question:

> *RQ1 What elements should be incorporated in an ideal framework for participatory sound interaction?*

We used the audience as an example to investigate the behaviors of subjects in a dialogue. We formulated and analyzed several interaction models mainly from audience participation forms and performance system types. We revealed that an immersive and ongoing interactive environment can be developed into an ideal framework. Therefore, audience, as the main subject of a dialogue, is able to initiate a dialogue at the lexical level by actively interact with the system. Such environment includes *a direct contribution of the audience as well as a responsive interaction*, which could provide the audience with direct auditory feedback on how they are engaged and influencing the performance. Accordingly, the audience is assisted to understand the dialogue at the semantic level with direct auditory feedback from interaction. Sound design, as the adjective of a dialogue, is the key element to complement the dialogue at the syntactic level. Additionally, we formulated a participation journey map to analyze and highlight two key components of the ideal framework: learning and interaction (see Figure 2.1). In conclusion, we consider this ideal framework as ***a responsive dialogue between the audience and the performance system, aiming to achieve a constant loop between interaction and learning*** (see Figure 2.4).

7.1.2 Interactive Sound System from Framework

We have utilized the ideal framework to develop both stochastic and deterministic interactive systems. In **Chapter 3**, we specifically focused on the development of a stochastic interactive system, the sound installation Băi, in response to the second question:

RQ2 Can we use an ideal framework to develop an interactive sound system?

On the basis of what we have discussed and concluded in Chapter 2, we intended to apply the ideal framework in Băi and examine whether an installation can constantly engage the audience through the interaction. A "pendulum" speaker has been used as an interactive interface for audience participation. The installation requires direct contribution of the audience and sound generation from the pendulum speaker gives the a clear environment to the audience to tack and understand the interaction. Together with a setup of six surrounding speakers, the installation offers a dynamic and spatially responsive sound environment for the audience to explore. Moreover, exercising too much control over the pendulum causes the installation to quickly spiral into chaotic and unpredictable behaviour. The unexpected movements of the pendulum speaker and sound results from the surrounding speakers may challenge the audience and keep the interaction continuous. This, in combination with the fact that some physical labor is needed to restrain the pendulum, leads to a tense dialogue between the audience and object, struggling for control. Meanwhile, the swinging movement in space makes it possible for multiple audience members to interact with the installation at the same time. The members in the audience may have influence on each other and form a more diverse interaction accordingly. Thus, ***an intense and ongoing interactive system is created by constructing a dynamic and responsive relationship between the audience and the installation using sound*** (cf. Figure 3.2).

Furthermore, the development of this stochastic sonification system contributes to answering the third research question:

RQ3 Can we develop an interactive sonification design that is intuitive to understand?

The term intuitive is defined as without the need for instructions (cf. definition 3.3). The algorithms are used to translate the motion of the pendulum into different modes of behaviour of the sound environment, in both direct and indirect ways. At first, it may seem that the real-time synthesized sounds react to the motion in a predictable manner, which could be easily understood by the audience as the first step. Especially the noticeable sound generated from the pendulum speaker, as well as the bell sound from the surrounding speakers. The implementation of excitement added variations to the interaction and sonification. The movements resulting from the interaction cause the sounds in the environment to change between different states of relative stability and chaos. However, the distinct audible characteristics for each state are not hard for the audience to discover. In conclusion, ***a distinguishable auditory feedback that directly reacts could assist the audience to comprehend the mappings between sound and data, accordingly explore the interactive sonification design in an intuitive way***.

7.1.3 Sonification Design from Framework

In **Chapter 4**, we addressed an interactive form of sonification with a deterministic character. To that end we considered molecular structures with a carbon backbone as a vehicle to investigate data sonification. With this approach we have further explored second and third research questions:

> *RQ2 Can we use an ideal framework to develop an interactive sound system?*

In order to provide listeners with direct auditory feedback, we used navigation as the primary mode of interaction, allowing them to perceive and track the changes in sound (cf. Figure 4.5). By sonifying a specific area surrounding an atom, we ensured that listeners could focus on a limited number of simultaneous sound objects, usually no more than four. Through an analysis of the potential flow of the listener's experience throughout participation journey map (cf. Figure 4.6), we concluded that ***interactive navigation is an effective approach that offers listeners the opportunity to explore the structure step by step, enabling them to learn and understand how the sound changes in response to the movements***. *This interactive form allows for an engaging and immersive experience where listeners can actively navigate the structure and discover the sound mappings.*

> *RQ3 Can we develop an interactive sonification design that is intuitive to understand?*

The term intuitive is illustrated as easy to learn and fast to recognize (cf. definition 3.3). Sonification design or sound design, therefore, plays a crucial role for the participants to understand. Essentially, each chemical element in the molecule has its own characteristic sound mapping to help and enhance the listeners to identify and localize in a molecular structure. We conclude that ***using a metaphor can help the listener to acquire the meaning of sounds fast as well as decrease confusion***, like building up a connection between atomic mass (light/heavy) and pitch (high/low). We proposed pitch as the main feature because the changes are easily perceivable and distinguishable. According to the atomic mass differences, the lighter element was mapped to a higher pitch while the heavier element was mapped to a lower pitch. We presented a population of designs starting with earcons and arriving at a model-based sonification. In that regard we discussed the possibility to achieve the immediacy of sound identification and localization. Finally, we ended with a pattern design of irregular impulses, which can assist the segregation of multiple concurrent sound sources.

7.1.4 Evaluation of Sonification Design

In **Chapter 5** and **Chapter 6**, our main focus was on evaluating the sonification design of concurrent sound sources, as described in Chapter 4, with the following question:

RQ4 How can we efficiently evaluate a sonification design?

We conducted two cycles of validations, where the evaluation methods were designed based on usability testing principles and aligned with the goals and hypotheses we had regarding the sonification design.

In Validation 1, the pretest-posttest design was sufficient to evaluate the learnability and effectiveness of the sonification design. Only the first layer (cf. definition 4.6) of sound was sonified because we aimed at whether the participants could learn the mappings between the sounds and elements and identify them. We used two different durations of recordings to evaluate the fast recognition of the sonified elements. Modifications on sounds have been implemented based on the results from Validation 1, for the purpose of improving the listeners' performance of identifying elements.

In Validation 2, we aimed to investigate how well the listeners are able to identify and localize two different layers of sound. We prepared two conditions of sound tests and used a within-subject design for the evaluation. In condition 1, only the first layer sounds were played and after 10 seconds the second layer sounds were added to them, In condition 2, the sounds of the two layers were played simultaneously from the beginning. The results collected from two conditions tests are valid to evaluate the factors that may influence the individual performance of the sound identification and localization, besides how many sounds listeners are able to hear and localize maximally. In conclusion, ***both validations effectively served the purpose of testing the design concept and exploring the variables, i.e. pitch, density and direction, that could potentially impact the identification and localization performances***. *The results were analyzed using statistical methods, which have contributed to the advancement of evaluation and provide a solid basis for future investigation in the field of data sonification.*

7.1.5 Navigation through Sonification

In this thesis we have discussed about interaction with sound, within the context of audience participation and data sonification. A responsive system can provide a bidirectional interaction for participation. Moreover the feedback from the system can assist the subject to better understand the interaction.

Sound can be a medium to convey information of data. In contrast to visual perception, sound perception offers a broader spectrum of elements for interpretation, including pitch, volume, duration, rhythm, and more (Malikova, Adzhiev, Fryazinov, & Pasko, 2020). Interactive navigation is a good way helping to understand such relation between sound and data. Therefore, considering navigation with respect to the sound interactions that we have studied seems appropriate.

Navigation, as a concept in interaction, follows the principles of attention; i.e. the classical sequence of orienting, searching, filtering and expecting. For the learning of a sound-based interaction, first the orienting, searching and filtering are important. We can see this for the molecular sonification where the sounds provide the clues for the positions of the atoms and the navigation over the molecular structure feeds the attention sequence. To enable navigation as a feature, we first need to evaluate whether a sonification design is understandable and learnable. Different experiments were conducted based on the specific features of the sounds we aimed to investigate. If the learning substantiates, the expecting is fulfilled and the sonification is internalized

Navigation is an essential aspect of understanding an information space. We have started from a simple information space, represented by a molecule, which had a limited number of data elements and thus limited navigation possibilities. Nevertheless, without the navigation, the structure of the data cannot be understood. With respect to this simple information space, we demonstrated that sound interaction can support navigation. In order for this to be efficient, an individual sound associated with a data element should be recognizable, assisting in the localization of the data element. These two sound features address the attention assets of orienting, searching, and filtering. The expecting asset comes with the understanding, which relies on following the reasoning from the sensitivity tuple. This reasoning allows for answering questions regarding the information space, i.e., "Where can I go from here?" and "How do I get there?" The reduced information space of a molecule serves as a good example to study this.

With the sound design that has been developed for the molecule information space, the understanding is deterministic. This should mean that repetitive learning will decrease the error rate.

If the information space has dynamics; the reasoning is more difficult. Such can be seen in Băi, which is stochastic in nature. From reasoning over navigation in Băi, some prediction can be accomplished and the dynamics of the sound mappings with respect to behavior of the system can be revealed. The interesting aspect of the system is that it will never be the same, only exhibiting similar behavior. This as opposed to the molecule information space, where the state space is limited and is completely defined from the beginning of the sonification. In the stochastic system, the sensitivity tuple is more difficult to comprehend as the dynamic operation of the system requires continuous adaptation and reflection by the subject.

Together, these two distinct information spaces, with their completely different state spaces, provide interesting information for sound design in interaction and sonification. They demonstrate two manners of interactive navigation. While the navigation in Băi reveals the comprehension of interactive behavior and sound mappings. The navigation in a molecular structure focuses on the perception and understanding of an information space through abstract sounds.

In both case, navigation is an important feature for understanding and comprehending the information space – in one case from movement to an abstract sound space (Băi) and in the other case from abstract sounds to an ideation of data (Molecule). To this end, we have put effort in the evaluation of the sonification design so as to assess if it is understandable and learnable. We have investigated the features of the sounds with different experiments accordingly. As long as the sound can achieve the aim of recognition and localization, the sonification design can be applied to an extended use. Our work has pioneered the use of sound in interactive virtual environments and paves the way for other sonifcation design with more complex information spaces, deterministic or not.

7.1.6 Dialogue for Sonification

The navigation process is guided by the dialogue system, which plays a crucial role in facilitating learning and interaction and providing feedback. We have acknowledged the importance of the dialogue and we develop the dialogue from three components. We have distinguished the verbal, the subject and the adjective part. The adjective part is responsible for the sounds produced by the system, serving as auditory feedback. These sounds offered in the dialogue enable the participant to infer over the interactions and reflect on the responses from the system. These three components together form the complete sonification experience.

The interaction and navigation have physical parts, in the dialogue this is the verbal part. Subjects are able to generate actions based on the verbal part, which typically offer affordances, like a pendulum (Băi) or a Graphical User Interface (Molecule). Through navigation and interaction with these affordances, participants gain understanding and receive feedback that allows them to make inferences about future states or next steps. So, in conjunction with the navigation, the dialogue contributes to making the system learnable and understandable. The design of the feedback, i.e. the adjective part, is crucial to make the system work. For this matter the sound element is pivotal in the system.

7.2 Future work

In Chapter 1-6 we have obtained key findings and presented conclusions regarding the chosen topics (i.e., interaction models, data sonification, interaction & design, evaluation of data sonification). Building upon these insights, we would like to extend the application of our current findings to broader interactive participation context including data and sound, like audience participation in museums or student participation in classrooms. Moreover, data analysis can be supported by the sound representation in laboratory settings. In this section, we will discuss about the possibility of future research.

Interactive Experience

We have explored and discussed a lot about interactive experience in various contexts. We are curious to know how the *ideal framework* can be applied in the context of exhibition, museum, classroom and lab, where includes audience participation. Therefore new ways of potential interaction involving visual and physical perception can be created for the visitors or participants. For example, it is worth exploring and evaluating the interactive experience using extended reality (XR) techniques, as these have the potential to enhance exhibits and installations, transforming museums into vibrant and dynamic spaces. During COVID-19 many museums were kept closed, while some of them started to organise online events and provide virtual tours as compensation. Such digital interactive experience without physically presence is an asset derived from this special period. Similar situations happened in the context of education. The rise of online learning brings the challenge of how to improve the efficient study experience of students with a more interactive and engaged virtual environment. It is a great opportunity to explore the possibility of interactive experience over distance or virtually, as well as to study whether a *responsive interactive system* can be developed in such context.

Virtual Auditory Environment

Nowadays, virtual reality explores possibilities to enhance human perception and extend their immersive experience not only with visual feedback, but also with audio, haptic and other sensory information. Mazuryk and Gervautz summarized several benefits that auditory information can offer from previous virtual reality research, amongst them are spatial orientation cues, perception ability of information that is outside of visual display, possibility of parallel perception of many information streams (Mazuryk & Gervautz, 1996). Novo pointed out that an Auditory Virtual Environment (AVE) is like a Real Auditory Environment, composed of sound sources, a medium and a receiver. It aims to create situations in which human perceive the auditory events that correspond to a virtual environment(Novo, 2005). In our study, the evaluation of the sonification approach not only provides valuable insights in the context of auditory display contributes to the broader field of AVE. Although the results we got from the experiments still require further development and testing, *the key findings regarding concurrent sounding sources, including localization, segregation, and identification*, are related to the research fields of both auditory display and AVE. Factors such as masking effects, immediate sound recognition and localization, and the exploration of maximum concurrent sources might play significant roles in these domains. Moreover, there is a potential development in the field of extended virtual experience such as auditory navigation, either using headphones or an ambisonic system. We believe that our research paves the way for future investigation and advancements in these fields.