OPENSPACE SONIFICATION: COMPLEMENTING VISUALIZATION OF THE SOLAR SYSTEM WITH SOUND

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ABSTRACT

Data visualization software is commonly used to explore outer space in a planetarium environment, where the visuals of the software is typically accompanied with a narrator and supplementary background music. By letting sound take a bigger role in these kinds of presentations, a more informative and immersive experience can be achieved. The aim of the present study was to explore how sonification can be used as a complement to the visualization software OpenSpace to convey information about the Solar System, as well as increasing the perceived immersiveness for the audience in a planetarium environment. This was investigated by implementing a sonification that conveyed planetary properties, such as the size and orbital period of a planet, by mapping this data to sonification parameters. With a user-centered approach, the sonification was designed iteratively and evaluated in both an online and planetarium environment. The results of the evaluations show that the participants found the sonification informative and interesting, which suggest that sonification can be beneficially used as a complement to visualization in a planetarium environment.

1. INTRODUCTION

Data visualization software is often used to explore the information of outer space. One example of this is the software OpenSpace [1], which is a collaboration project between Linköping University, the American Museum of Natural History and NASA. With this software, the user can explore outer space by interacting with a three-dimensional representation of the universe and specifically the Solar System. OpenSpace is commonly used in planetariums, where a presenter narrates the visuals of the software together with background music [2]. The music is used to immerse the audience and evoke a sense of wonder, but it does not relate to the information presented visually or add any additional insight. In similar software this data would instead be visible in information windows, but this would not be a suitable way of presenting the information in a planetarium show. OpenSpace does not output any sound, which is a missed opportunity as sound could be used to further engage audiences and create a more immersive [3] and emotional experience [4]. Furthermore, by adding sound that reflects and expands on the information shown visually, the audience could gain further knowledge and understanding about the Solar System [5]. This can be done by utilizing sonification [6], which is the use of non-speech sound to convey information. It can be seen as the aural counterpart to visualization, and can therefore be used together with the visuals of OpenSpace to create a more informative and immersive experience.

The aim of the present study was to implement and integrate a sonification with OpenSpace to convey information about the Solar System and increasing the perceived immersiveness for the audience in a planetarium environment. A sonification was implemented conveying planetary properties such as the size and orbital period of a planet by mapping them to sonification parameters. The sonification was designed in multiple steps and evaluated both online as well as in a planetarium. The results suggest that sonification can be beneficially used in a planetarium environment.

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2. BACKGROUND AND RELATED WORK

Because of the differences of the senses, sonification has the potential to perceptualize certain concepts better than a visual representation. Compared to vision, auditory perception has a better ability to detect temporal changes [7]. This can be useful when conveying the periodicity of the Solar System, such as the rotational and orbital periods of planetary bodies.

While our eyes are mainly capable of focusing on things that are in front of us, our ears can detect and focus on changes all around us, enabling the sound to be positioned in a wider space than visual components. This enables the possibility to position sound around an audience, which can increase the sense of presence and immersion [3]. In a planetarium, this can enable auditory positioning of planets where these appear visually.

Human hearing is capable of perceiving and distinguishing between several sounds simultaneously, which can be used to convey multivariate data in an intuitive way [8]. It is also possible to focus on one of many audio streams, relating to the Cocktail Party phenomenon [9]. There is however a difference between perceiving several sounds and actually absorbing the information. In several studies, it was shown that listeners could attend to at least three auditory streams at the same time [10]. Comprehending these different auditory streams can be improved if the sounds are spatially separated, as shown by Song and Beilharz [11], where a separation of 120 degrees between two audio streams gave an increased comprehension when these were simultaneously presented to listeners (see also discussions by Litovsky [12]). Consequently, it is important to balance between providing enough auditory information without overwhelming the audience, as well as using positioning to facilitate separation between sound sources in the sonification.

There are a few studies where sonification has been used in planetariums that served as an inspiration to the present study. Quinton *et al.* [13] sonified the planets of the Solar System with a focus on testing and demonstrating it for the end user. A plan-

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etarium representative was initially interviewed to select the most important planetary properties. These properties were mapped to sound parameters such as pitch, loudness, tempo, and timbre. An evaluation was conducted with 12 participants where they were tasked with discerning properties for each planet by listening to the sonification without any prior knowledge of the sound design or which planet they were listening to. The results of the evaluation showed that the participants could discern several characteristics about some of the planets, but it was also concluded that 3 out of 8 planets were not represented successfully. The authors stated that the use of surround sound is effective at sonifying orbital periods, as the planets could orbit around the audience. For this work there was no visual component, but the authors stated that the inclusion of it would benefit the sonification.

The second planetarium study is the work done by Tomlinson *et al.* [14]. It shares some fundamental aspects of the work by Quinton *et al.* [13]. For example, similar relevant planetary properties were concluded by interviewing astronomy teachers of different levels of science classes. The sonification was divided into two views, the *Solar System view* and the *Planetary view*, in which different information of the planets were conveyed. An evaluation of 40 participants was conducted in a planetarium, where images of the planets were used for visual context. The evaluation included a survey of five questions concerning how interesting, pleasant, helpful, understandable and relatable the sonification was experienced. The variety of questions shows that for an evaluation of sonification it is not just important to assess how well information is conveyed, but also how it is perceived aesthetically. The survey was later developed into an audio user experience scale named BUZZ [15]. The results from the evaluation showed that the sonification managed to relay information to the audience while also being pleasant and interesting to listen to. The dissertation by Tomlinson [16] provides further insight into this topic.

An interesting difference between these studies are in their sound design. Tomlinson *et al.* [14] focused on straight-forward mappings, creating individual sonifications for each planetary property. Quinton *et al.* [13] instead created one continuous sound that conveyed several planetary properties simultaneously. Both of these approaches to sonification have advantages and disadvantages, where straight-forward mappings and separate sonifications might provide a more intuitive and informative experience, while a composition of several sonifications might provide a more pleasant and immersive experience. For the present study it was intended to explore the design space between these two approaches to create both an informative and immersive sonification.

3. METHOD

The design process of the sonification began by studying which planet properties were suitable to be sonified. Unstructured interviews with OpenSpace developers were initially held to identify which planetary properties would be suitable to be sonified together with OpenSpace. Most concepts were however obtained from related work [13, 14], where planetarium representatives and astronomy teachers were interviewed about which aspects of astronomy were the hardest to teach. Specifically, the planet properties that were of most importance were mass, type of planet, length of day, length of year, distance to the sun, gravity, and temperature. All of these properties were included for the sonification of the present study except for distance to the sun, since this was deemed to already be conveyed in an intuitive way using the visuals of OpenSpace. The atmospheric pressure and average wind speed of the planets were added to convey more detailed information about the planets. Data of all of the properties were acquired from NASA's planetary fact sheets[1]. Common mappings that had previously been used in other sonifications [17] were used as a starting point to map the properties, while at the same time experimenting with new mappings and drawing inspiration from related work [13, 14]. The chosen planet properties and their respective sonification mappings are shown in Table 1.

Since there are eight planets in the Solar System it would not be possible to convey the information of all the planets at the same time. The sonification was therefore developed to consist of two views, the *Solar System view* and the *Planetary view*, following the approach by Tomlinson *et al.* [14]. The *Solar System view* (see Figure 1) provided an overview of the Solar System, presenting the sonification of mass, length of day, and length of year of several planets at the same time. The *Planetary view* (see Figure 2) focused on a single planet, offering a more close up view and more sonifications. In addition to mass and length of day, the *Planetary view* presented the sonification of gravity, temperature, atmospheric pressure, average wind speed, and moons of the planet. Additionally, a compare functionality was implemented to act as a combination of the views mentioned above, where the view of the Solar System was combined with the sonifications used in the *Planetary view*. This allowed the comparison of all sonifications for two planets at the same time, which were enlarged to visually highlight the comparison.

Planet Property	**Sonification Mapping**
Mass	Pitch
Length of day	Tempo of oscillation
Length of year	Spatial positioning
Gravity	Bouncing ball analogy
Temperature	Intensity of sizzling
Atmospheric pressure	Depth of wind sound
Average wind speed	Fluctuation of wind sound

Table 1: Planet properties with respective sonification mappings.

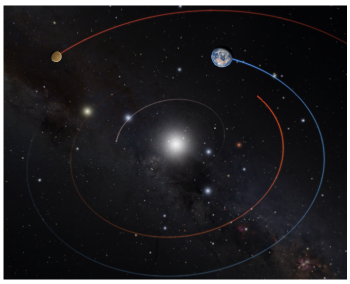

Figure 1: The *Solar System view* of the inner planets, where a comparison is made between Earth and Mars.

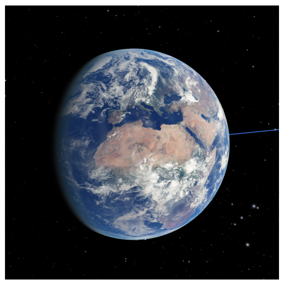

Figure 2: The *Planetary view* of Earth, showing a close up view and conveying details of the planet.

[1]NASA's planetary fact sheets:
`https://nssdc.gsfc.nasa.gov/planetary/factsheet`
`https://solarsystem.nasa.gov/planet-compare`

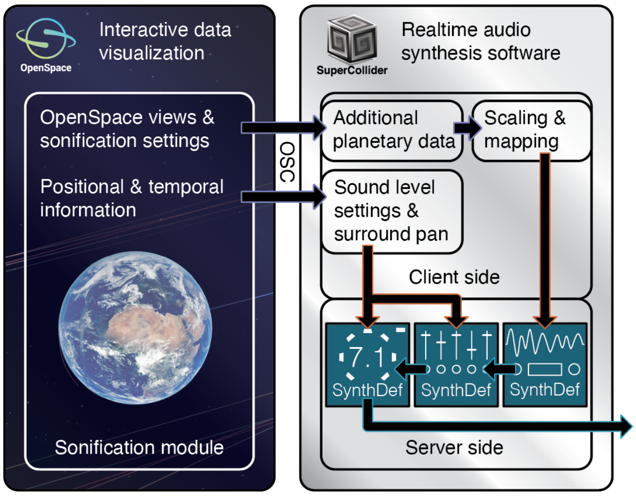

Figure 3: Structure of the sonification with synth definitions, and integration with OpenSpace over Open Sound Control (OSC).

3.1. Integrating the Sonification

The sonification was produced by using the real-time audio synthesizer SuperCollider [18]. A synth definition was created for each sonification in SuperCollider and was only changed by the variables of the planets' properties to create a comparable environment. To integrate the sonification with OpenSpace, the positional and temporal data from the software was used in SuperCollider to reflect what was shown visually (see Figure 3). The amplitude of the sound was mapped to the distance between the camera and the planet in the *Planetary view*, the surround panning of the sound was mapped to the position of the planets displayed visually, and the tempo of the sound was mapped to the time speed in OpenSpace. This was done by extracting the necessary data from OpenSpace and sending it to SuperCollider in real-time using the protocol Open Sound Control (OSC) [19].

The graphical user interface in OpenSpace was extended to control the sonification to enable more interactivity. This enabled the user to filter which sonifications were used in the *Planetary view*, which planets were sonified in the *Solar System view*, as well as selecting which planets and sonifications to compare using the compare functionality. However, by leaving every sonification turned on, the user could explore all of the sonifications simply by visiting the planets using OpenSpace.

3.2. Sound Design

Considering the repeatable nature of the planets' rotations and orbits, the sonification was designed as a parameter mapping sonification where most of the sounds were looping in sync with the rotation of the planet. This enabled the listener to get a sense of the mappings in a matter of seconds for most of the planets, and it also enabled the possibility of playing several sonifications of a planet simultaneously. However, the sonifications were equally designed to be listened to individually, by using different kinds of mappings and sound design. The sonification can be listened to here[2].

[2]Link to video of the sonifications: `https://vimeo.com/528822742`

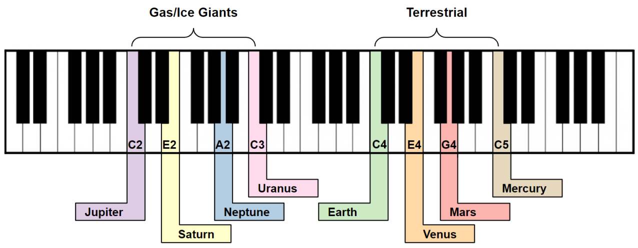

Figure 4: The chosen tones for the planets in the Solar System.

Mass was mapped to the pitch of the fundamental sound of the planet, such that a larger planet had a lower pitch than a smaller one, according to the polarity mappings for sizes of objects [20]. A three-octave range (C2-C5) was used when deciding the pitches of the planets. The lowest octave was dedicated to the gas and ice giants, and the higher octave was used for the terrestrial planets. This created a gap of one octave between the type of planets which represented the differences in size between the inner and outer planets. The planets were assigned to tones within their respective octaves depending on the mass of the planet, which is shown in Figure 4. The type of the planet decided which waveform was used as its fundamental sound. For a terrestrial planet, a sawtooth wave was used to represent the higher density of these planets with a sharper sound with more overtones [21], and for a gas/ice giant a square wave was used which created a more mellow tone to represent the lower average density of these planets.

To convey the **length of day** of a planet, an analogy of a spinning object was used. If a sound emitting source is attached to a spinning spherical object, the sound is occluded and muffled when facing away from the listener. This creates an oscillation of frequency content and amplitude level with an added Doppler-effect [22], similar to the sound of a Leslie speaker. This makes it possible to appreciate the speed of the rotation by listening to the tempo of the oscillation. The oscillation was implemented by modulating the fundamental sound of a planet with a resonant low pass filter, where the speed of the modulation depended on the length of day of the planet. This resulted in a change in timbre as well as in loudness, creating an impression of night and day, i.e. of darkness and brightness, to support the perception of length of day [23, 24, 25]. The default timescale was set to 24 hours per second (i.e. one Earth-day/second) to make the sonification suitable to be listened to in real-time. This could be changed by the user by changing the simulation speed in OpenSpace.

Length of year was conveyed through the spatial positioning of the planets. The length of year of a planet determined how long it would take to pan the planet around the surround sound system and back to its original position. Using the positional data extracted from OpenSpace, the surround panning of the sonification for a planet followed the visual representation of the planet in OpenSpace. This enabled the planets to revolve around the audience both visually and aurally in a planetarium environment. The orbits of the moons of the planets were also conveyed in this way in the *Planetary view*.

The sonification of **gravity** was based on a physical model of a bouncing ball, similar to Tomlinson *et al.* [14]. This acted as an auditory icon, where the gravitational force of a planet was mapped to the gravity parameter of the physical model, causing the ball to bounce less frequently and for a longer time for a planet with lower gravity. Since mass is related with the gravity of an object, the pitch of the ball sound was set to be the same as in the mass sonification. Panning was applied to the sound of the ball so it would be perceived that the ball was bouncing sideways to create a wider stereo image. The ball was dropped every fourth rotation of a planet, except for Mercury and Venus since they did not fit within the temporal scope because of their much longer length of day. Instead, they had a similar timing of Mars and Earth respectively.

Temperature was conveyed with a noise impulse generator, where a higher temperature increased the rate of the impulses. This created a sizzling sound that increased in intensity with a higher temperature, that could either be linked to the sound of a frying pan or fire crackling. To convey temperature change, the interval of the lowest and highest temperature of a planet was used to modulate the rate of the impulses. This was done in sync with the length of day of the planet, such that the highest temperature is audible during the daytime for a fixed position on the planet, and the lowest temperature is audible during nighttime. The modulation created a sweep of varying rates of impulses, which was further emphasized by the addition of a band-passed noise. For planets without a temperature interval the mean temperature was used instead, which resulted in a constant rate of impulses.

Atmospheric pressure and **average wind speed** were conveyed with a synthesized wind sound, which was created by randomly modulating the cutoff frequency of a low-pass filtered noise to create the dynamics of a wind sound. The surface pressure of a planet was used as a measure of the atmospheric pressure. As this measure varied to a high degree between planets and did not apply for the outer planets that lack a defined surface, the atmospheric pressure was determined by a ranking of both the surface pressure and type of planet. The amount of low frequency content in the wind sound was mapped to this ranking, with a lower and deeper sound for higher atmospheric pressure. The wind speed of the planets varies between different atmospheric levels and the surface, and the amount of wind speed data is different between planets, therefore a mean value of the wind speed was used for each planet. The amount of fluctuation of the wind sound was mapped to the average wind speed of the planet, with more fluctuation with greater wind speeds and more static sound for lower wind speeds. The sonification was disabled for the planet Mercury to convey that it does not have a defined atmosphere.

The sound design of the sonifications for the *Solar System view* was simplified to convey information of several planets at the same time. This was done by using brown noise through a band-pass filter where the center frequency was set to create a pitch according to the mass of the planet. The pitch used was the same as in the *Planetary view*, but increased with one octave for all of the planets, both to signify that the planets appear smaller on the screen, and to better fit with the brown noise. Instead of using a sweeping low-pass filter to convey the length of day as used in the *Planetary view*, an amplitude modulation was used, similar to Tomlinson *et al.* [14]. The moons of the planets were sonified in a similar way in the *Planetary view*, apart from the sonification of length of day where a pulse oscillator was used instead to trigger a sound every time the moon had completed one orbit around its planet.

3.3. User Evaluation

Two different types of user evaluation were used to evaluate the sonification. Two online surveys were conducted during the design process to get feedback which was primarily used to improve the sonification. The final evaluation was conducted in the dome theater at Visualiseringscenter C in Norrköping, Sweden, a planetarium which houses a 7.1 surround sound system and was the target platform for this study. The sonification of length of year, the *Solar System view*, and moons were not included in the online surveys since they could not be evaluated without a surround sound system, while all sonifications were evaluated in the dome evaluation. For all evaluations, the audio user experience scale BUZZ [15] was used, which is a questionnaire used to evaluate sounds that are part of an auditory display. The questionnaire contains 11 statements that covers the functionality, comprehension, and aesthetics of sounds. Each statement is scored using a Likert scale of 1 (strongly disagree) to 7 (strongly agree), which was also used when answering the other questions in the surveys.

The **online surveys** contained a series of videos, where each video included a comparison of one sonification between two planets. A description of the sonification mapping and the differences of the two planets was presented together with each video. For most of the sonifications, a second video example of two other planets was added to give further insight to the respondent. After watching the videos of one sonification, the respondent was asked to answer questions regarding how well the sound represented a certain fact, such as: *"Mars has a smaller mass than Earth, how well do you think the sound represents this?"*. Before moving on to the next sonification, the respondent had the opportunity to give free text answers. This process was repeated for all of the sonifications. For the last video, all of the sonifications of Earth were played at the same time, and the respondent was asked to answer how well they could distinguish the different sonifications, and how well they thought the sounds fitted together. To conclude the survey, the respondent was asked to answer the BUZZ questionnaire about the overall experience.

The **dome evaluation** started with the test administrator informing the participants of how the test would be conducted. OpenSpace was introduced without the sonification, which was done to familiarize the participants with the visual experience so that the focus would be on the sonification during the evaluation. The participants were asked to rate how immersed they felt, which also was asked at the end of the evaluation as a measure of whether the sonification increased the experienced immersiveness. The evaluation proceeded by evaluating each sonification individually, similarly to the online surveys. The test administrator first explained the sonification mapping and then demonstrated the sonification. The sonification for Earth was played first as a reference, followed by two other planets to enable the participants to hear how the sonification changed depending on the planet. In conjunction with this, the difference of the planets compared to Earth was revealed by the test administrator so that the audience could later rate how well they thought the sonification conveyed the differences of the planets. The questions for the sonification were then introduced to be answered by the participants individually in an online form. While the participants answered the questions, the sonification of the three planets would be played through again sequentially to enable more time reflecting on the sounds. This process was repeated for every sonification. The *Solar System view* was evaluated by playing the sonifications for the inner planets and Jupiter at the same time, and letting the participants rate the mappings of this view. The sonification of moons was evaluated in a similar way using the five major moons of Uranus. After all of the sonifications had been demonstrated, the participants answered the BUZZ questionnaire about the overall experience.

3.4. Participants

Respondents of the online surveys were recruited using the website *SurveySwap*[3], a service where researchers swaps surveys with each other. A total of 64 unique respondents were part of the two online surveys, 30 in the first and 34 in the second. The country of origin of the respondents was mixed and spanned all over the world. 72% (n = 46) of the respondents used headphones to listen to the sonifications, while the rest used other devices such as external speakers. The self-perceived knowledge of the Solar System for the respondents had a mean value of 3.4 (1-7). 26 free text answers were given in the first survey, compared to 11 in the second survey.

A total of 30 unique participants attended the dome evaluation across 8 evaluation sessions with around 5 participants each, which were seated around the center seats of the planetarium. The participants were recruited through mailing lists to staff and students of Linköping University. The self-perceived knowledge of the Solar System for the participants had a mean value of 4.7. 102 free text answers were received during the dome evaluation.

4. RESULTS

The results of the evaluations were divided into the types of included questions. The first type of questions considered how well the participant could discern the information of the planets through the sonification. The second type of questions regarded the selected BUZZ statements that were answered for every sonification, which were added after the first online survey. The third and last type of questions regarded the full BUZZ questionnaire, which was answered at the end of each evaluation and dealt with the overall experience of the sonification.

The results are presented as boxplots, where 50% of the data is presented inside of the box, and the rest is distributed along the upper and lower quantiles. The thick horizontal line in the box represents the median value and the **x** represents the mean value. Even if presenting means for ordinal values is not that common, it appears as useful to present [26] as it provides additional information about the distribution of data [27].

4.1. First Online Survey

The results of the first survey showed that the sonifications could convey information in a reasonably good way, see Figure 5. The sonification of length of day had the highest mean score of 5.5, while the sonification of mass received a lower mean score of 4.2 (1-7). Free text answers stated that the respondents would associate a smaller mass with a higher pitch, which was consistent with the chosen pitch mapping.

The results of the BUZZ questionnaire for the first online survey are presented in Figure 7, where it can be seen how the respondents rated the overall experience of the sonification. The sonification was experienced as interesting, receiving the highest mean score of 5.3, while the pleasantness of the sonification received one of the lowest ratings with a mean score of 3.9. It could however not be determined from the quantitative results which sonification was considered the most unpleasant apart from analyzing the free text answers. Therefore, for the second survey, three selected BUZZ statements were added to the survey regarding how pleasant, interesting and understandable the sonification was perceived, which were answered after each sonification.

4.2. Second Online Survey

Based on the findings of the first survey, the sound design was changed according to the feedback of the free text answers. The gravity parameter was decreased equally for all planets in the gravity sonification to make the bounces of the ball more distinguishable. The sonification of atmospheric pressure and wind speed was modified to increase the perceived difference between the planets. Finally, the sound design for the temperature sonification was adjusted to be more pleasant.

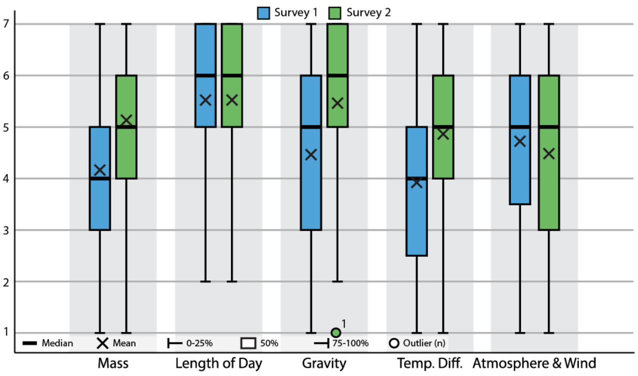

Figure 5: Ratings of how well the respondents thought each sonification represented the difference of two planets in both online surveys.

The median value for how well each sonification could convey information was either improved or remained unchanged for all of the sonifications compared to the first online survey, see Figure 5. The mean score for the sonification of gravity increased from 4.5 in the first survey to 5.5 in the second survey. The sonification of atmospheric pressure and wind speed had a decrease in mean value, with free text answers mentioning that it was not as well represented as the other sonifications.

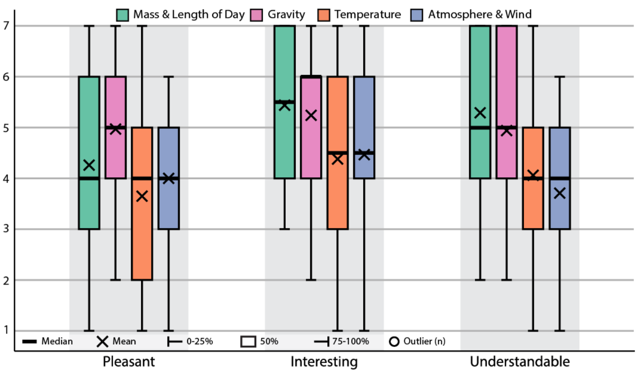

Figure 6: Ratings of the selected BUZZ statements for the second online survey.

[3]SurveySwap: `https://surveyswap.io/`

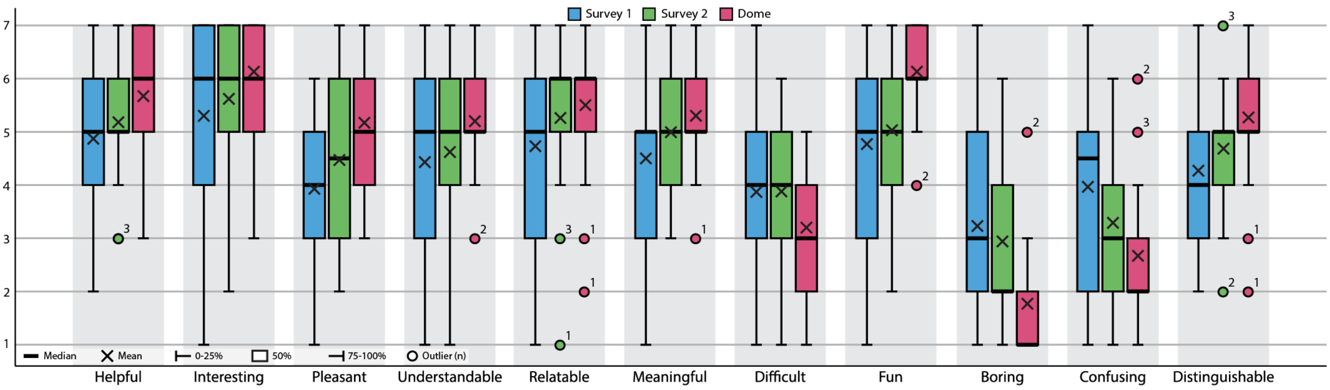

Figure 7: Ratings of the BUZZ questionnaire for the overall experience of all of the evaluations. Note that Difficult, Boring and Confusing are negatively worded statements, where a lower rating is better.

The results of the selected BUZZ statements is shown in Figure 6, where mass and length of day were considered the most interesting and easy to understand, while the sonification of temperature was considered the least pleasant sound with a mean value of 3.7.

For the overall experience of the sonification in the second online survey (see Figure 7), it can be seen that the ratings improved for all of the statements in the BUZZ questionnaire compared to the first online survey. The statements regarding how confusing and relatable the sonifications were had the biggest improvement in mean value.

4.3. Dome Evaluation

For the dome evaluation, every sonification got a mean score above five, except for the length of year and the sonification of the moons, regarding how well each sonification could convey information, see Figure 8. The length of year was harder to discern according to the free text answers since the speed of the orbits were too slow to fully appreciate. It was also mentioned that the spatial positioning of lower pitched planets was harder to interpret. The surround effect itself was described as *"...awesome, though. Hearing the planets around you was almost mesmerizing."*. Similar opinions were given for the sonification of the moons, since it shared the same mappings as the *Solar System view* sonifications. Regarding the aesthetics of these sonifications, one participant stated that it *"Sounded more like music"*.

A possible trend can be seen in the results of the selected BUZZ statements (see Figure 9), where less pleasant sonifications such as mass and length of day were considered more understandable, while more pleasant sonifications such as for the *Solar System view* and the moons were considered harder to understand.

The dome evaluation received the highest score regarding the overall experience compared to the online surveys, see Figure 7. The sonification was considered interesting and fun, both receiving the highest mean score of 6.1. How difficult the sonification was to understand improved in comparison to the online surveys, but still received the lowest rating with a mean score of 3.2.

When all sonifications were played simultaneously for one planet in the *Planetary View*, participants rated a mean score of 5.8 of how well they could distinguish the different sounds, and rated a mean score of 5.2 to how well they thought the sounds fitted together. 67% (n = 20) of the participants rated that their sense of immersion was increased with the sonifications included, compared to when only the visuals of OpenSpace were presented in the beginning of the evaluation. When asked if the participants would have appreciated if sonification was used during a public planetarium show, 83% (n = 25) said that they would appreciate it.

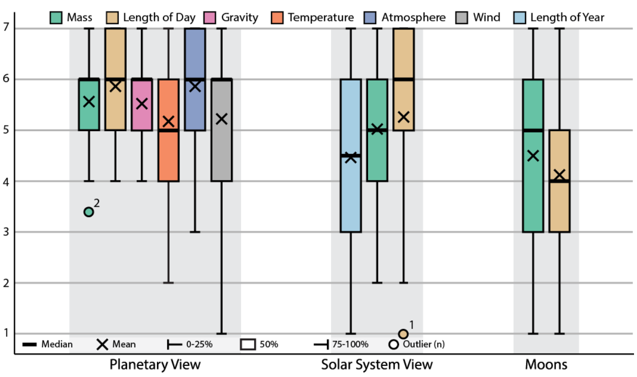

Figure 8: Ratings for the questions regarding how well the participants thought the sonification discerned the differences between the planets in the dome evaluation.

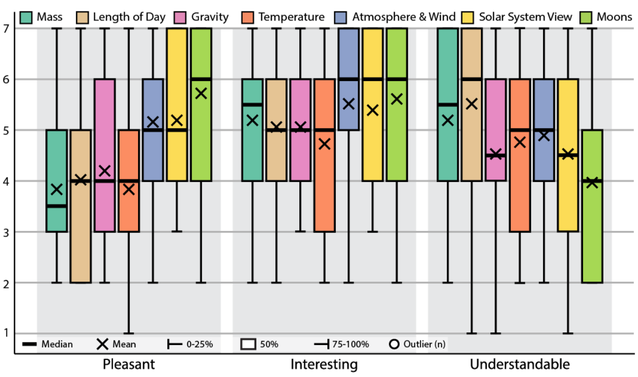

Figure 9: Ratings of the selected BUZZ statements for the dome evaluation.

5. DISCUSSION

The aim of the present study was to use sonification to complement OpenSpace to convey information about the Solar System, while also creating an immersive experience. The results showed that the participants thought that the sonification was informative and interesting, and by comparing the results of each evaluation it can be seen that the iterative process improved the sonification. By introducing users early in the design process, both the sonification and the evaluation were refined to create a better end result. For many sonifications used in the present study, it seemed that the sound design changes created a positive outcome.

The opinion for some sonifications remained unchanged across all of the evaluations however, such as the sonification of temperature which was considered one of the less pleasant sonifications. This was improved between the evaluations, but in general the idea of the sonification was that a planet with a higher temperature would be perceived as more intense, which could also be interpreted as unpleasant. The motivation for this sound design choice refers to the discussions conducted by Quinton *et al.* [28], where it is argued that the sound design of sonification should not entirely be aimed towards making a sonification pleasant to listen to, but instead to be as efficient and relatable as possible.

The evaluation results of the dome evaluation showed a trend between how pleasant and understandable the sonifications were perceived, see Figure 9. This might suggest an interesting design challenge, where the comprehension of a sonification might be negatively related with how aesthetically pleasing the sonification is perceived to be. Free text answers for the dome evaluation mentioned that the more pleasant sonifications (*Solar System view* and moons) sounded more like music, which from an aesthetic point of view might be considered as positive. However, this might not necessarily be the case when it comes to trying to convey information, since listening to music could be more of a passive experience. For more information on sonification and music, see discussion by Vickers [29]. This in part was the motivation of adding a selection of the BUZZ statements after each sonification, to have a quantitative measure on the atheistic aspects of each sonification. Fewer free text answers were given overall in the second survey, which might suggest that the added questions in the survey made it possible for the respondents to express their opinions fully without adding free text answers.

The difference in rated experience between the sonifications could also depend on the different sound designs used. The sonification of mass and length of day had direct mappings to pitch and tempo, with decreased pitch for a larger planet and increased tempo for a shorter length of day. These strict and direct mappings were experienced as understandable but also as less pleasant compared to the experience of for example the sonification of atmosphere and wind speed. This sonification was instead mapped indirectly to the data, where an increased atmospheric pressure increased the lower frequency content and an increased wind speed increased the fluctuation of the wind sound, creating more of a soundscape than a direct and simple sonification. As a result, these sonifications were experienced as quite pleasant to listen to, but less understandable. These examples of the experience of the sonification designs refers back to the chosen design space in between the related work with more direct mappings [14], and more abstract and indirect mappings [13].

How fun and boring the sonification was experienced improved the most in the dome evaluation compared to the online surveys, which suggests that sonification in a planetarium environment is more fun and engaging compared to an online environment. The quality of the listening environment in a planetarium probably also affected the perception of the sonifications. For example, because of the dedicated subwoofer in the dome theater, the sonification for atmospheric pressure might have been better reproduced since it depended more on lower frequencies compared to the other sonifications.

The surround positioning for the sonifications might also have had a part in how fun and engaging the sonification was perceived in the dome theater. The informativeness of the surround positioning was however not entirely evaluated, since the sonification of length of year was not evaluated successfully. The sonification was interpreted as too slow by the participants to experience the change of position in relation with how long it was listened to, since the same time speed of 24 hours per second was used. It was also not evaluated individually, since the sonification of mass and length of day for the *Solar System view* was evaluated at the same time as length of year. By creating a separate demonstration of length of year and increasing the time speed for this sonification would have created a more representative case to be used in an evaluation.

The positive ratings of how well the participants could distinguish several sonifications of one planet simultaneously suggest that multivariate data can be conveyed in an intuitive way with sonification. Together with surround positioning [3], this also allowed playing the sonifications of several planets at once, displaying a range of information that would be harder to do through a visual representation.

The evaluations focused mostly on the experience of listening to the sonification in a planetarium. Since OpenSpace is as much of an interactive experience as a passive one, it would for future work be interesting to study how a user explores the Solar System themselves by interacting with the software. This would put more focus on evaluating the graphical user interface, and possibly coming up with more ways to sonify astronomical data in an interactive environment. It would also be interesting to further explore how sonification supports learning, and if it provides a stronger basis for knowledge building compared to visualization alone. Similarly, future research could further explore the use of sonification for providing a more immersive experience in a planetarium as compared to the use of no sound [30].

6. CONCLUSION

The aim of the present study was to explore how sonification could be used as a complement to a visualization software to convey information about the Solar System, as well as increasing the perceived immersiveness for the audience in a planetarium environment. A sonification of the Solar System was implemented and integrated with the visualization software OpenSpace, and was evaluated both online and in a planetarium environment. By implementing and evaluating iteratively, the sonification and evaluation method was refined to cater to the end user. The results of the evaluations showed that sonification can be beneficially used as a complement to visualization in a planetarium environment. The results also suggest that a trade-off might be present between how informative and aesthetically interesting the sonifications were perceived, such that a more pleasant sound became harder to understand and vice versa, and that this should be taken into consideration for future design processes.

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