Sonification Analysis Methods by Utilizing Translation Strategy*

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Abstract

The prevalence of sonification works for astronomy research and education has notably increased [1], with the Sonification Handbook outlining multiple strategies for implementing mappings of data to sound [2]. However, a definitive evaluation framework for the mappings is lacking. To address this issue, translation strategies can be used as a method to assess sonification outcomes since sonification can be regarded as a form of intersemiotic translation according to Jacobson [3]. First, a literature review and practice review were conducted on comprehensively analyse sonification mappings according to Vinay and Darbelnet's seven translation strategies. Second, two empirical experiments were conducted using a tool developed to sonify star data and enable the observation of stellar features through sound. Results showed that sonification mapping strategies can be a novel classification method to improve description reproducibility. It also enhances the perceptibility and interpretability of sonified astronomical data. These results contribute to the field of sonification, offering a new perspective on the design and evaluation of auditory displays for astronomical data and data in general.

Keywords

Sonification, Intersemiotic Translation, Translation Strategy

1. Introduction

The prevalence of sonification works for astronomy has notably increased. Despite advances in sonification research, the field lacks standardised analysis methods, resulting in challenges related to research replicability. This research aims to address this gap by proposing a standardised sonification methodology, incorporating principles from translation studies into the discipline.

Sonification is defined by Hermann as "the data-dependent generation of sound if the transformation is systematic, objective, and reproducible" [2]. This widely accepted definition is often used for the term sonification itself, and this paper is no exception. The disciplines of sonification are exceptionally broad in scope, including HCI, music, acoustics, psychology, the arts, and ergonomics [2, 4, 5]. According to the Sonification Handbook, there are five categories of sonification, including audification, parameter mapping sonification, auditory icon, earcon, and model-based sonification according to the Sonification Handbook [2]. Parameter mapping sonification (PMSon), the second category, which "represents changes in some data dimension with changes in an acoustic dimension to produce a sonification" [2]. This paper focuses on PMson among the five categories of sonification and the term "sonification" also indicates PMson in this paper. This research integrates translation studies into the field of sonification to address existing challenges. Sonification serves a variety of purposes across different domains. Even though sonification researchers have developed theories for the sonification discipline, a definite evaluation framework for mappings is still lacking. Zanella et al. [1] stated that there is a "lack of systematic published evaluation of the usefulness and effectiveness of sonification in general". This gap limits the systematic investigation towards and application of sonification in general. Additional challenges in the field have been identified by multiple researchers. Terasawa [6] stated that there needs to be

6th International Conference on Creative\Media/Technologies (IConCMT), November 27-28, 2024, St. Pölten, Austria
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clear methodological guidance, and Quinton et al. [7] pointed out the lack of description of the decision-making processes for sonification design.

To address these challenges, we propose integrating concepts from intersemiotic translation into sonification analysis. Translation studies are an interdisciplinary field concerned with the theory, practice and phenomena of translation [8]. Translation is "the transference of the meaning of one language to another" [9]. In addition, "a language is a kind of 'signifier of something' that exists without limit" [9]. From this view of language as "a signifier of something", the translation of a non-linguistic signifier into another signifier is called intersemiotic translation. Jakobson identified three types of translation, with intersemiotic translation being particularly relevant to our work [3]. In fact, intersemiotic translations between literature and film and between painting and film studies have been discussed as semiotic results among the arts. In 1959, Jakobson stated, "intersemiotic translation is an interpretation of verbal signs by means of signs of nonverbal sign systems". Expanding on this concept, Koller describes intersemiotic translation as "caught between the requirement to be faithful to the original texts and the need to transform them into texts that are understood and accepted in the target culture". This process, he argued, represents "a dynamic and functional event that transcends culture" [10]. Following Koller's idea of intersemiotic translation, we can interpret sonification as a dynamic and functional event that transcends culture, caught between the need to transform data (the original text) into sound (the target text) that is understood and accepted by the target culture.

The structural similarities between translation and sonification processes further support this theoretical integration. According to Nida [11], Figure 1 shows that the process of translation takes the source of information, (analysis), transfer (restructuring), and the receptor. In addition, Figure 2 present a communication model of sonification in three terms [2]: 1. There is an information source, 2. There is an auditory display that converts it into a communicative form, and 3. The receiver of the obtained information is shown. These models reveal fundamental parallels between sonification and translation processes. This is because although the source of information differs between the language and the numerical data, the process by which the transfer of meaning takes place and teaches the recipient is the same for sonification and translation.

In this study, translation studies are integrated to address the lack of a formal description framework for sonification for two reasons. The first reason that sonification can be considered as translation is that the definition of intersemiotic translation can be interpreted in the context of sonification. The second reason is that the communication model of sonification is analogous to sonification and translation. To create the evaluation framework, Vinay and Darbelnet's seven translation strategies are utilised, which are explained in Section 3.1.

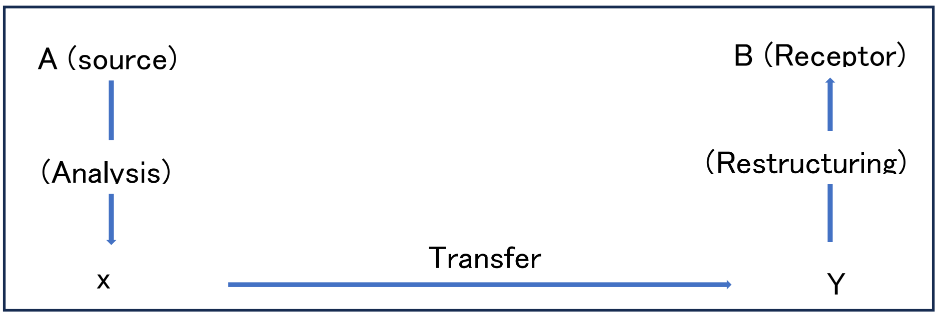

Figure 1: Nida's process of translation [12]

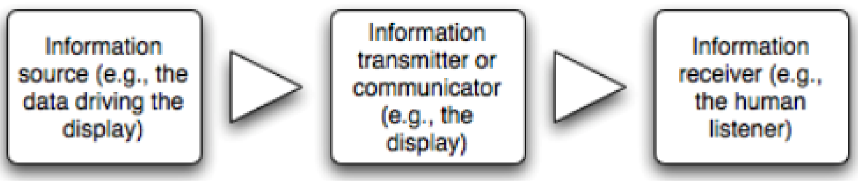

Figure 2: Communication model for sonification [2]

As a case study to evaluate the proposed framework, we present our approach to providing an alternative way of accessing astronomical data using sonification, specifically designed to benefit individuals who are blind or have low vison (BLV).

In recent years, there has been a significant growth in astronomy-related sonification projects. Zanella et al. [1] documented this trend, noting eight to nineteen new astronomy sonification projects emerging every year. This analysis includes 98 projects posted to the Sonification Archive website and tagged with astronomy. According to Zanella et al. [1], only 13% of astronomy-related sonification projects primarily aimed to improve accessibility for individuals who are BLV, and 22% considered it a secondary objective. In addition, 8.2% of the project's purposes were education. Our study also focused on individuals who are BLV and examined the use of space data sonification in astronomy education. Education in this context encompasses both formal education and lifelong learning, which includes school, home-based learning, social education, cultural activities and personal interests [12]. According to a national survey in Japan, only 32.8% of respondents indicated that lifelong learning opportunities for visually impaired individuals include accessible venues and study programs [12]. This suggests that BLV individuals face significant barriers when studying astronomy. Developing tools and programs that facilitate learning in this field could enhance their educational opportunities. Previous studies on astronomy education using sonification for visually impaired learners are presented in Section 2.1.

2. Related Work

This study explores the application of spatial data to enhance accessibility and education for individuals who are BLV. Furthermore, it examines research on sonification and its implications in the field of translation studies. Before addressing these two topics, it is essential to first discuss the mapping of sonification and the framework for evaluating sonification. Dubus et al. analysed 179 scientific publications to identify trends in sonification research [4], revealing the various physical and auditory domains commonly utilised in sonification studies. Historically, Stephen Barrass demonstrated the effectiveness of the TaDa approach in his doctoral dissertation [13]. The TaDa approach is an integrated methodology that addresses a range of issues by employing a multifaceted system that incorporates principles from human-computer interaction (HCI), visualisation, graphic design, and sound design. Frauenberger and Stockmann [14] evaluated the design framework "PACO" by analysing design frameworks presented in the proceedings of ICAD. Classic mapping topologies in sonification include one-to-one, one-to-many, and many-to-one mappings [2]. For example, one study conducted a controlled experiment comparing four different elevation sonification mappings: absolute, unsigned relative, signed relative, and binary relative. Another study explored mapping strategies in musical performance and sound processing, focusing on three examples: Synth, a general mapping strategy, and the sonification of gestures. While mapping strategies have been explored in various contexts, they often exhibit biases towards specific target domains, and many of these strategies remain in preliminary or underdeveloped stages. Given the current stage of undevelopment in mapping strategies, this study employs frameworks from translation studies to investigate the potential and applicability of mapping practices.

2.1. Astronomical Sonification for BLV

Both theoretical and applied studies have been undertaken in the field of astronomical sonification targeting BLV. Theoretical research primarily examines cognitive responses to sound, while applied research focuses on developing tools and methods for BLV. In addition, discussions have also been conducted to advance research on individuals with BLV [15].

Sound plays a crucial role in BLV individuals in perceiving and analysing data. Deandra et al. [16] introduced an image sonification program as an alternative to screen-based research, enabling BLV users to experience astronomical images through sound. Using Python, the program converts shapes into MIDI files, which are later refined into MP3s. Evaluations of visually impaired participants show that, with practice, this sonification approach effectively enhances accessibility to astronomical images. One notable tool in this domain is xSonify, software that converts scientific data into acoustic sequences [17]. This tool provides accessibility for visually impaired people to fully participate in the field of space science, a field traditionally dominated by visual data exploration methods.

Additionally, NASA has been showing astronomical data sonification on its website [18]. Kimberly Kowal Arcand et.al explored how NASA data have been translated into sonification, enabling the public to experience astronomical phenomena aurally [19]. It examines participant's responses to this sonification, considering educational and cognitive influences. The study highlights how sound representations can enhance understanding and interest in space science, especially for people with visual impairments, while providing a new sensory dimension for all audiences to explore the universe. At the end of this paper, Arcand et.al stated, "Translating data into sonification is similar to translating language". This sentence supports this research's assertion.

2.2. Translation Studies and sonification

One study investigated the relationship between data and sound in sonification, framing it as a form of translation. Lepri [20] analogically compared sonification with translation studies and identified the notion of negotiation in the process of transforming source data into target sound. This notion of negotiation offers an alternative perspective on the relationship between data and sound. Furthermore, the author highlights that a compromise made during the sonification design process can serve as a mediation between data and sound. Building on this perspective, this study also focuses on the relationship between data and sound by integrating strategies from translation studies to establish a method for sonification analysis.

3. Method

This section introduces the aims of the research and outlines its two primary steps. This study evaluates the effectiveness of astronomical sonification in astronomy education and advocates for the application of translation strategies in sonification analysis. One key indicator of effectiveness is whether the sound evokes the imagination of a star. Effectiveness is determined whether participants can perceive and "image" the temperature and brightness of stars based on sonified data used in the study. In this case, "imagining" differs from "visualising" in that it involves a broader cognitive process. While visualising typically refers to the mental creation of clear, concrete images or scenes in one's mind, imagining encompasses a more abstract and expansive form of thought. It can involve envisioning situations, emotional experiences, or conceptual scenarios without the need for specific visual representation. In this sense, imagining can engage other senses and cognitive domains, such as sound, feeling, or even intangible concepts, to explore possibilities beyond the immediate sensory world. This perspective is supported by Gaut's definition: "For one can imagine various states of affairs without being committed to their truth or to carrying them out, so one can try out various options" [21]. The term "education" in the research refers to lifelong learning, as opportunities for lifelong learning are often limited to individuals who are BLV [13]. This highlights the importance of supporting lifelong learning for BLV individuals by developing tools and creating opportunities to explore topics, such as astronomy on their own terms. Moreover, lifelong education tends to be more casual than school education and often targets older learners.

The central research question is: How can the analysis of sonification using translation strategies reveal the relationship between data and sound in parameter mapping sonification? This research question is addressed through two steps, which are detailed in the next section.

3.1. Parameter Mapping Sonification Strategies

The first step in this research involves creating parameter mapping sonification strategies using Vinay and Darbelnet's seven translation strategies (Table 1). These strategies are selected because Vinay and Darbelnet's seven translation strategies focus on a local translation approach, unlike the global translation strategy supported by Venuti and others. This localised approach aligns well with the research focus. In this study, the translation in sonification specifically refers to the process of converting data to sound synthesis, with an emphasis on data processing and sound synthesis. Figure 3 illustrates the parameter mapping sonification process, which involves localised translation from data preparation to sound synthesis. Notably, the sound design is excluded from the translation process in this research. Since the study focuses on the translation of the sonification mapping process, it does not account for the aesthetics of sounds such as the listener's emotion, or comfort to subjective responses, despite their recognised importance [22].

Data processing is categorised into four higher-level processes: reduction, integration, shift, and extraction. As no existing classification for sonification data processing types was found, these categories were synthesised by the author based on the sonification handbook [2]. The processes are defined as follows:

- Reduction refers to the process of simplifying a dataset that is either too large or overly complex, by converting it into a more manageable and comprehensible form. This process ensures that only the most relevant information is retained.

- Integration refers to the process of merging or combining different numerical values within a dataset to form a cohesive, unified representation. This technique is particularly beneficial when working with datasets that contain fragmented or isolated elements, as it allows for the consolidation of diverse data points into a more coherent structure. Integration helps in creating a comprehensive view of the data, enabling better analysis and interpretation, especially when disparate pieces of information need to be connected or aligned.

- Shift refers to the process of adjusting numerical values within a dataset by moving them upward or downward in a fixed increment. This transformation is useful for aligning the data with specific auditory dimensions or scales, facilitating better synchronisation with predefined thresholds or ranges. By shifting the values, the dataset is modified in a way that ensures it conforms to desired patterns or aligns with auditory representations, all while preserving the integrity of the used data.

- Extraction focuses on selectively removing certain elements or subsets from the dataset. This step allows for the isolation of specific data points that are deemed relevant to the sonification process.

In addition to data processing, auditory dimensions are classified into five higher dimensions: pitch, timbre, loudness, spatial, and tempo, as identified in prior research [4]. While these auditory dimensions can be further subdivided, this study focuses on their higher-level classifications.

Table 1

Vinay and Darvelnet's 7 translation strategies [9, 23, 24] SL means Source language, TL means target language.ST means source text, and TT is target text.

#	Term	Definition
1	Borrowing	The SL word is transferred directly to the TL. e.g." Frankfurter Würstl" or "Haggis" can be translated as it is in TL.
2	Calque	The SL expression or structure is transferred in a literal translation. e.g. A German English calque would be Ohrwurm/earworm, an English German one skyscraper/Wolkenkratzer.
3	Literal Translation	Word-for-word translation e.g., English ST "I left my spectacles on the table downstairs" can be "J' ai laisse mes llunettes sur la table en bas" in French.
4	Transposition	This is a change of one part of speech for another without changing the scene. e.g. noun: they have pioneered -> they have been the first.
5	Modulation	This changes the semantics and point of view of the SL. e.g. You can have it -> I'll give it to you
6	Equivalence	To refer to cases where languages describe the same situation by different stylistic or structural means. e.g. As blind as a bat -> Blind wie ein Maulwurf
7	Adaptation	Changing the cultural reference when a situation in the source culture does not exist in the target culture.

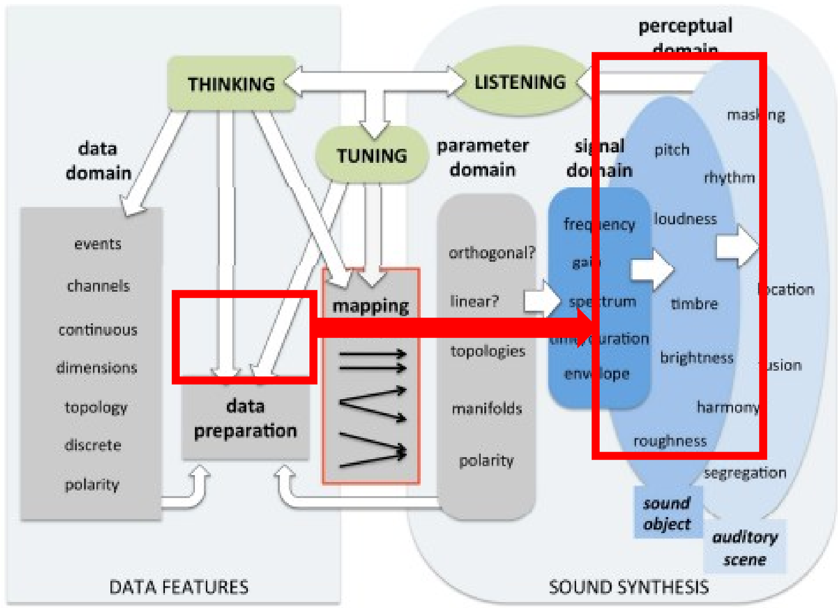

Figure 3: Parameter mapping model made by Florian Ground and Jonathan Berger [2]. Modified by the author.

3.2. Listening experiment

The second step of this research involved conducting listening experiments using a sonification tool called SoundObservation. The outcomes of these experiments are intended to inform the analysis of sonification mapping strategies developed in the first part of the research.

The experiments were conducted at the planetarium of Sendai City Observatory. This location was chosen because the observatory has a history of implementing planetarium initiatives for visually impaired individuals and shares a similar vision of making astronomy accessible to this demographic. Additionally, the Sendai City Observatory is actively engaged in educational efforts and the promotion of astronomy. It has published several research reports on disseminating knowledge in the social sciences to blind and low-vision (BLV) individuals. Given its expertise and alignment with the research goals, the observatory was approached for assistance in conducting the experiments.

The participants in this study were four visually impaired individuals affiliated with “Star Hope”, a continuous employment support organisation located in Sendai City. All participants were congenitally blind though they varied in age. Participant selection was facilitated by a representative of the organisation to ensure suitability for the experimental conditions. Ethical approval for this study was obtained from the Ethics Committee of the Tokyo Institute of Technology (Approval No. 2023164).

The interviews conducted during the experiments were analysed using Steps for Coding and Theorisation (SCAT), a qualitative analytical method described in [25]. The SCAT analysis involves constructing meta-descriptions within a matrix and coding them in four sequential steps:

1. Extraction of significant words and phrases from the original data.
2. Paraphrasing the extracted words or phrases with terms from outside the dataset.
3. Explain the phrases in terms of their context or background information.
4. Thematising, where overarching themes or constructive concepts emerge from the data.

The results from step 4 are synthesised to create a cohesive storyline. This is an example of a storyline from the interview recorded, “Participant B was asked about their ability to perceive differences in stellar characteristics. Then, participant B responded that they could detect differences in the luminosity of stars based on variations in pitch. From this, following storyline emerges: “Using the astronomical data sonification tool, sound frequencies were understood to represent differences in the luminosity of stars”. The SCAT method was chosen for its ability to qualitatively analyse small datasets, which is critical given the limited number of participants in this study. The question investigated in the listening experiment is what kind of mappings are effective in conveying stellar information to BLV people. The term effective is defined as the participants imagined stars. Also, further notices from participants are interpreted as more effective.

3.3. The tool SoundObservation

The SoundObservation system [26] was utilised in the experimental phase of this research. The mapping and sound design aspects deviated from the referenced citation; only the system itself was utilised. The implementation process began by acquiring real-time stellar data, including coordinates, distance, temperature, and brightness, from the Hipparcos satellite data catalogue. This dataset was selected due to its comprehensive nature and accessibility, which provides high-resolution information for more than 120,000 stars. The star data used in constellations were further supplemented by information obtained from AstroCommons [27].

To create the experimental setup, stellar data were plotted within a virtual starry sky using Unity, a game engine. Each star was positioned according to its coordinates to generate a realistic simulation of the night sky. The participants’ head orientation was tracked using a 6-axis sensor embedded in the headphones they wore. The directional data were transmitted from Unity to Max for Live via Open Sound Control (OSC). Simultaneously, the stellar information was converted into sound using Ableton Live Suit**e** and Max for Live, and the resulting audio transmitted wirelessly to the headphones via Bluetooth. The system ensured that the sound corresponding to the star the participant faced was played through headphones, creating an interactive and immersive experience.

The validity of the data used in this experiment was carefully evaluated. The Hipparcos satellite data was chosen for its accessibility and exhaustive content, with all data available for download by the public. Additionally, the use of AstroCommons, a resource licensed under Creative Commons (CC), ensured compliance with data-sharing and adaptation policies, provided proper attribution was given. The combination of these sources provided a robust foundation for the experiment, as the Hipparcos dataset contains essential information such as stellar positions, temperatures, brightness, and size.

The specific stellar attributes incorporated into the system were selected for their relevance to observational astronomy and their significance in the sonification process. The positions of the stars were critical for plotting them within the virtual space and determining the audio output direction. Temperatures, brightness, and sizes of stars were also included as key measurable properties that contribute to the generation of meaningful auditory representations.

This integration of usage and sonification provided participants with an innovative and accessible means of interacting with astronomical data. The use of real-time tracking and dynamic audio feedback allowed for a nuanced exploration of how sound can effectively convey stellar information.

4. Results and discussion

In this section, two investigation findings are presented. These experiments were conducted using previously outlined methods. Additionally, these results are analysed and discussed in detail. In the listening experiments section, these “[]” are the extracts directly from the SCAT analysis results.

4.1. Parameter mapping sonification strategies

Table 2

Parameter mapping sonification classification

#	Translation Strategies	Definition	Sonification strategies
1	**Borrowing**	The SL word is transferred directly to the TL.	Sound data is transferred directly to sound. e.g. sound data to sound via speaker.
2	**Calque**	The SL expression or structure is transferred in a literal translation.	Shifted sound data is translated literally to pitch or loudness. e.g. sound wave (earthquake data) is shifted up to a hearable range of frequency.
3	**Literal Translation**	Word-for-word translation	**Shifted data** is directly proportional to **pitch or loudnes**s. Faithfully adhere to one-to-one correspondence. e.g. data 1-4 is directly considered as 1 to 4 dB.
4	**Transposition**	This is a change of one part of speech for another without changing the scene.	**Data dimensions or data are extracted, integrated, reduced** and converted to **pitch or loudness.** e.g. data 440 to 442 represents the main feature of data out of 10 numbers. Therefore, 440 to 442 are extracted and converted to 440 to 442 Hz.
5	**Modulation**	This changes the semantics and point of view of the SL.	**Data dimensions or data are extracted, integrated**, reduced for the **selection of timbre**. e.g. data from 0 to 7 is reduced and only odd numbers are used for the selection of waveform such as sine wave and sawtooth wave.
6	**Equivalence**	To refer to cases where languages describe the same situation by different stylistic or structural means.	**Data are extracted, integrated, shifted, reduced, and converted** to **spatial position.** e.g. numbers 10 to 12 are shifted down from 1 to 3 and it is converted to the position of speakers.
7	**Adaptation**	Changing the cultural reference when a situation in the source culture does not exist in the target culture.	**Data are shifted, extracted, reduced, or integrated** and converted to **sound effects or tempo.** e.g. average number is used for tempo bpm.

This section presents the results of mapping sonification strategies using Vinay and Darbelnet's seven translation strategies (see Table 2). The sonification process considered five auditory dimensions—pitch, timbre, loudness, spatial positioning, and audio effects according to the previous research data processing strategies: shift, reduction, extraction, and integration. This framework assumes a direct transformation from data preparation to sound objects, as outlined in the Sonification Handbook. Among these five auditory dimensions, pitch, timbre, and loudness are directly associated with the characteristics of the sound waveform, such as amplitude, frequency, and wavelength. Consequently, in this study, they are regarded as higher-order parameters compared to spatial positioning within auditory dimensions. Moreover, the audio effects and tempo exert an indirect influence on the sound wave and are not intrinsic to the original composition. As a result, they are classified as the lowest-dimensional parameters within the framework of sound parameter analysis.

One may question whether Borrowing and Calque align with the definition of sonification. However, given that these strategies involve mapping elements to sound parameters, they can be considered rudimentary forms of sonification in this context. Additionally, this mapping serves as a classification of the direct relations between data and sound, rather than an analysis requiring consideration of psychological acoustic components. As discussed in Section 3.1 on parameter mapping sonification strategies, this approach is limited to the direct translation of processed data into sound parameters. In this context, such considerations are not necessary. Borrowing and calque in translation exhibit similarities to the "direct transformation" approach in sonification. In both cases, mappings are established mechanically and systematically, such as "this data corresponds to this pitch" or "this structure corresponds to this rhythm." These mappings focus on the physical relationship between data and sound, neglecting the listener's psychological response. As a result, the acoustic transformation does not convey semantic meaning or interpretation; rather, it emphasizes the physical correspondence between data and sound, which, similar to the translation techniques, remains "direct" in nature. Table 2 presents a classification of the relationships between the data, their corresponding numerical representations, and their mapping to sound. Not all datasets can be selected arbitrarily by the individual conducting the sonification. The selection of strategy is inherently influenced by the numerical range of the data. For instance, directly mapping values within the range of 1 to 200 to a decibel scale (1–200 dB) would be inappropriate. In such cases, the raw data must first undergo preprocessing before being mapped to a corresponding auditory parameter, thereby constraining the range of applicable sonification strategies. Thus, it is important to acknowledge that the selection of sonification strategies is, to some extent, dependent on the characteristics of the original dataset.

The subsequent listening experiments employed four translation strategies: literal translation, transposition, modulation, and adaptation. The next points provide a detailed examination of literal translation, transposition, modulation, and equivalence to clarify the usage of the strategies while deliberately excluding adaptation.

- The third strategy Literal Translation**:** In its original context, "literal translation" refers to the direct conversion of words and phrases from the source language (SL) to the target language (TL) with a one-to-one correspondence. In sonification, this is interpreted as data being directly proportional to auditory dimensions such as pitch or loudness, maintaining a one-to-one correspondence. For example, numbers 1 to 4 could directly correspond to 1 to 4 dB.

- The fourth strategy transposition: this strategy, initially defined as changing part of the message (e.g., converting a noun to a verb) without altering the meaning, was adapted in sonification to involve extracting, integrating, shifting, or reducing data to correspond to auditory features like pitch or loudness. For example, data points 440 and 442 may represent the main features of a dataset, with the values extracted and mapped from 440 to 442 Hz.

- The fifth strategy modulation: in translation, "modulation" involves altering the conventions of words to align with the target language's perspectives. In the sonification context, data dimensions are manipulated—extracting, integrating, shifting, or reducing data—to facilitate the selection of timbre. For instance, when dealing with a large dataset, such as data ranging from 0 to 7, the set might be reduced by selecting only odd numbers, which are then used to determine the choice of waveform (e.g., sine or sawtooth waves).

- The sixth strategy equivalence: originally, equivalence described the same situation being expressed in different syntactical structures across languages. In sonification, equivalence means extracting, integrating, shifting, or reducing data and converting them into spatial positioning. It is essential to recognise that regardless of the type of information processing performed, the mapping of sound to spatial parameters, such as sound imaging, adheres to the principle of equivalence. For example, if numbers 10 to 12 are shifted to the range 1 to 3, they may then be mapped to the positions of speakers in the auditory space.

Vinay and Darbelnet's seven translation strategies evolved from more literal to freer forms of translation, ranging from literal translation to adaptation. Additionally, borrowing in this context is closer to direct translation. Among these seven strategies, direct translation is often considered a reliable approach for translation. However, when literal translation proves to be ineffective or meaningless, indirect translation strategies may be employed, as noted by Vinay and Darbelnet [28]. The output style, whether in translation or sonification, is determined by the strategy chosen by the translator (or sonificator). In sonification, for instance, the choice of strategy directly influences the characteristics of the resulting sound. This variation in approach allows for an analysis of how different strategies can be employed to communicate the message more effectively, depending on the listener's perspective. Moreover, it provides insight into how the sonificator's interpretation of the data influences the sonification process, thereby shaping the auditory representation of the data.

4.2. Listening Experiments

In the second part of the methodology, listening experiments were conducted with four congenitally blind participants selected by employees from an employment support facility. Three participants were involved each day at the Sendai Astronomical Observatory. After experiencing the sonification tool, semi-structured interviews were conducted, followed by a qualitative analysis of the results.

First, we utilise key stellar parameters, including the distance from the star to Earth, temperature (represented by the B-V colour index), and spectral classification. These fundamental attributes serve as the foundational knowledge for understanding stars. Among them, spectral classification, determined using the Morgan-Keenan (MK) system, categorises stars based on their temperature, identifying them as self-luminous celestial bodies. By classifying stars, it becomes possible to construct diagrams that approximate their evolutionary trajectories, predicting future changes in temperature, size, and brightness.

In this study, these stellar parameters were mapped onto specific auditory properties. Spectral classification was associated with the selection of sound waveforms (sine or square waves), the isopycnic class was mapped to volume, the B-V colour index (representing colour) was also linked to volume, and the distance from Earth was mapped to reverberation. The rationale for this mapping is based on the analogy between sound and light as wave phenomena: in this context, the wavelength of sound corresponds to pitch, while light wavelength corresponds to colour. Thus, the translation of light waves into sound waves forms the basis of this mapping. Additionally, since reverberation is influenced by spatial characteristics, a greater distance from Earth was represented by an increase in echo intensity, simulating the spatial effect of distance through auditory perception. This analogy presupposes that when the data is visualised, the corresponding elements are identical.

First, the distance-from-Earth data used for reverb mapping originally ranged from a minimum of -0.077 to a maximum of 0.00134. These values were processed to define the range over which the reverb effect is applied. Similarly, the spatial data volume had a minimum value of -1.44 and a maximum of 6.65, which was mapped to a reverb effect ranging from 0 to 1 through the process of Adaptation. Given the use of audio effects, this mapping approach is referred to as adaptation. Additionally, the volume setting was mapped within a range of -1.44 dB to 6.65 dB. For pitch, the minimum input value ranged from -0.269 to a maximum of 1.865. These values were shifted to a minimum of 0, then scaled by a factor of 200, and mapped to frequency. This processing method, which involved shifting and scaling the data, corresponds to the technique of Transposition. Finally, given that there are seven types of spectral classification, seven waveforms were designed, each representing a combination of sine and sawtooth waves, allowing for categorical selection based on spectral classification. The first listening experiment employed four mappings: adaptation, literal translation, transposition, and modulation. Specifically, equivalence was used for translating distance to reverb, literal translation for luminosity to loudness, transposition for temperature to pitch, and modulation for spectral type to waveform (Table 3).

Table 3
Mappings of the first listening experiment

Strategy	Data	Sound Dimension
Adaptation	Distance	Reverb
Literal Translation	Luminosity	Loudness
Transposition	Temperature (B-V)	Pitch
Modulation	Spectral Type	Wave type

The feedback obtained from the participants after the experiments revealed two distinct interpretations regarding their ability to perceive the [characteristics of stars] through sound. One group of participants believed that it was possible to discern differences in the characteristics of stars through sonification, while another group, although able to perceive pitch variation, did not feel that it contributed to understanding the characteristics of the stars.

Participant B expressed, [I slightly understood the differences in characteristics for each star] and noted that it was [possible to feel the difference in luminosity as volume]. However, Participant B also acknowledged, [Although the answers are somewhat vague, there is something to be learned from the sonification process]. This suggests that Participant B was able to perceive differences in the characteristics of stars, although their understanding remained somewhat ambiguous. In contrast, Participant C, who possessed musical experience, remarked, [The sound I heard is composed of an A-major scale], and described the sonification as [musical] and [audible in a way similar to music]. Despite perceiving variations in pitch, Participant C concluded, [Even if the pitch variable changed, it was incomprehensible through hearing, and in practice, it was impossible to understand], further stating that they [only perceived the high and low of the pitch]. Additionally, Participant C described the experience as [melodic] and [pleasant] when changing the direction of their face, indicating that while they could perceive pitch changes, these changes did not correspond to the characteristics of the stars. On the other hand, Participant C commented, [There were no changes other than pitch] and noted that the system's sound was composed of [an A-major melody], indicating dissatisfaction with the lack of variation in sound beyond pitch. They expressed that the system's explanation was insufficient, which contributed to their dissatisfaction with the functionality of the system.

In conclusion, the feedback highlights the need for clearer explanations and improvements to the sonification experience to enhance its effectiveness in conveying astronomical characteristics. The feedback also underscores the necessity for a more comprehensive system and application interface to improve user understanding. The results of the first listening experiment revealed diverse interpretations of the mappings. Participants expressed dissatisfaction with the mappings, suggesting that their understanding of the sonified data varied significantly. For instance, some participants interpreted pitch as representing differences in star luminosity, others perceived variations in sound frequency as indicative of the distance from Earth to the star, while others believed that variations in volume corresponded to changes in luminosity. In response to these varying interpretations, the mappings were re-evaluated and adjusted for the second experiment. It became apparent that when pitch was used in a transpositional context, it acquired a more discrete quality, leading participants to perceive the sonified sounds as musical.

The interviews conducted during the first experiment emphasised the importance of providing clear instructions regarding the mappings prior to the sonification experience. It was determined that clear explanations are crucial to ensure more accurate and consistent interpretation of the sonified data.

Table 4
Mappings of the first listening experiment

Strategy	Data	Sound Dimension
~~Adaptation~~	~~distance~~	~~Reverb~~
Transposition	Luminosity	Loudness
Literal Translation	Temperature (B-V)	Pitch
~~Modulation~~	~~Spectral Type~~	~~Wave type~~

Improvements in the mappings were evident in the second listening experiment in which transposition was implemented for the luminosity-to-loudness translation (Table 4). This adjustment led to participants expressing greater confidence in the connection between stars and sound. For instance, some participants stated that [volume leads to a prediction of star luminosity] and that [imagining luminosity from differences in pitch] facilitated a clearer understanding of the sonification.

Participant C answered [a question about his impressions] regarding [the system for vision-independent astronomy and culture learning]. [Comparison with the previous experiment] and answered that there were [areas for improvement]. The [idea about good points] is that [differences in sound characteristics] can be [perceived]. In particular, [the audible star data], [changes in sound volume] [part of the system description] could be [largely understood]. During the experience, [speculation on the star's luminosity] was also carried out. Experimental Participant B said that there were [a variety of stars] and that he [felt satisfied] regarding [perception of star characteristics]. The [understanding of the mapping explanations] was [understandable]. When asked if they had a [substantial understanding of the individual differences], they had a [substantial understanding] and gave [examples of understanding beyond that]. When asked if they had a [perceptual understanding] of the [mapping from star to sound], they said that they [imagined] the [temperature of the loudest star] during the experience and that they had [improved understanding] [compared to the previous comparison], in which [understanding of specifications] was achieved. Regarding [other impressions], there were suggestions regarding [examples of system applications]. In the current system, [mapping between light/dark and sound volume] was given as [most perceptible], and respondents answered that they could clearly understand [differences in sound volume]. As a [post-experience request], the [request for SO] is to fulfil [the desire to understand the shape of stars]. This SO told them that [considerable imagery is possible].

When asked to [understand the difference in audible sound], experimental participant D made progress in [understanding it as a slight difference in sound] and thought about [the correspondence between pitch and luminous intensity] during the experience. In particular, he [recognised the presence of stars] and remembered them as [impressive sound volume] as [impressions of the experience]. During this conversation, we also discussed [examples of the translation from sound to star characteristics]. However, he confided that [forgetting of data and characteristic correspondence] occurred with regard to the content of [commentary at the beginning of the experience]. Regarding [thoughts during the experience], [at the same time as thinking about the stars], [the sound of the commentary was memorable], but during the experience, there was [difficulty in sorting out the sound]. By [listening to the mapping commentary at the beginning], I was able to gain [a sense of understanding of the information about the stars], which was [somewhat enjoyable].

Literal translation was employed for the temperature-to-pitch translation, which proved particularly effective for blind or visually impaired (BLV) participants. These participants found it easier to relate both the luminosity-to-loudness and temperature-to-pitch mappings to their understanding of astronomy. Several participants reported that the mappings allowed them to imagine stars and recall constellations, including first-magnitude stars, as a result of the changes in the mappings. This suggests that their existing astronomical knowledge was complemented by the sonification process. Moreover, the use of transposition, compared to literal translation, was perceived as more abstract in terms of the relationship between data and sound. Consequently, it appears that Transposition may be a more effective strategy for conveying information about star luminosity to BLV participants.

The findings of this study suggest that the use of transposition is potentially more effective for representing star luminosity, particularly in the context of sonification for blind or visually impaired individuals. Future studies should further define and standardise mapping strategies to ensure reproducibility and consistency in decision-making regarding sonification mappings. It is essential to note, however, that these strategies do not guarantee uniform experimental outcomes. Given that not all mappings were tested in this study, additional research is required to refine and standardise the approach for greater consistency and effectiveness in sonification methods.

5. Conclusion

This research addresses the lack of standardised methodologies in sonification by incorporating principles from translation studies. To address the absence of systematic evaluation frameworks, parameter mapping sonification strategies were developed using Vinay and Darbelnet's seven translation strategies. The primary aim of this study waswao evaluate the effectiveness of astronomical sonification for educational purposes by applying translation strategies to analyse sonification mappings. The central research question explores How can the analysis of sonification using translation strategies reveal the relationship between data and sound in parameter mapping sonification? The study followed a two-phase approach. In the first phase, sonification mapping strategies were created. These strategies enable the identification of optimal approaches to effectively convey information based on the listener's interpretative abilities. Furthermore, they reveal the sonificator's interpretation of how data inform the translation process, a perspective often missing from traditional research. In the second phase, listening experiments were conducted and analysed using the SCAT method. Three significant findings emerged from this phase. First, sonification strategies provide a novel framework for classifying mapping methodologies, thus filling a gap where no systematic classification previously existed. Second, these strategies clarify whether the relationship between data and sound is effectively conveyed or remains ambiguous, distinguishing between abstract and concrete interpretations. However, such distinctions have not traditionally been emphasised in the evaluation of sonified outputs. Lastly, the findings highlight the potential to enhance the reproducibility of mapping communication and provide a consistent framework for describing sonified outputs across different research contexts. It is important to emphasise that these results do not serve as a validation of the mapping itself, but rather as an evaluation of the effectiveness of the strategy employed.

In conclusion, this study demonstrated the value of integrating translation strategies into sonification analysis. This study highlights the potential of sonification mapping strategies to improve interpretability, reproducibility, and educational application of sonified data.

6. Future work

This study was conducted with a limited sample size of four participants. Although the analysis is qualitative, the small number of participants suggests the necessity of larger-scale studies to more accurately determine which mappings preserve the semantic integrity of the data and are most effective for facilitating the imagination of stars. Additionally, the experiment focused on two mapping strategies: literal translation and transposition. Future research should include an evaluation of other strategies, such as modulation, equivalence, and adaptation, to achieve a broader understanding of their applicability and effectiveness. Vinay and Darbelnet's translation strategies served as the foundation for developing the sonification mapping strategies in this study. Future work will aim to establish purpose- or skopos-oriented sonification strategies, along with emotionally prioritised mapping strategies. Moreover, integrating psychological frameworks into the sonification process will enable the identification of mappings that emphasise emotional and affective engagement, thereby enhancing the interpretability and emotional resonance of sonification.

Strategic mapping methods are currently endorsed by several researchers, many of whom are grounded in psychoacoustics. While considering the listener's perception and auditory comfort is essential, it remains questionable whether the conveyed sound accurately represents the underlying data. Regardless of the specific purpose of sonification, a crucial perspective is ensuring that the listener can comprehend the meaning embedded within the sonified data.

Acknowledgements

This work was supported by JST SPRING, Japan Grant Number JPMJSP2106 and JPMJSP2180.

7. Bibliography

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