DATA AND INFORMATION TRANSMISSION IN THE CONTEXT OF SONIFICATION

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ABSTRACT

This paper illustrates the significance of the concept of information as a tool to expound sonification design. Previous works approached the concept of information systematically. However, its structural characteristics during the process of sonification have not been thoroughly discussed. In order to address the above, this paper presents a framework based on the definition of information from the fields of physics, communication engineering, cybernetics, and systems theory. According to this framework, the representation of a phenomenon into organized sound becomes possible by the propagation of organization within the components of the sonification communication model. Moreover, a distinction between the terms data and information is proposed and related to well-established sonification techniques (Audification, PMSon, MBS). The structural characteristics of the phenomenon (described in terms of entropy) are linked with sonification functions leading to new perspectives of sonification design.

1. INTRODUCTION

Sonification has profound informative purposes as it conveys information [1] offering a relay between the information source and the receiver [2]. However, information is still often used as an abstract concept. Although sonification supports an information processing activity [3], the term information is still being used without concrete content. The problem lies in the uncertainty about the concepts of data and information, the way they are used in the sonification community, whether their distinction actually matters, and whether sonification should concern itself with one or the other [4].

The study of information becomes an academic trend ([5, 6, 7]). Scientists do not treat information as a slippery concept, but rather explore its physical nature and relate its use in different disciplines leading to an organized theory. Information is not only the outcome of the examination of a phenomenon but also a physical quantity [8] that creates organized structures [9].

The link between information and sonification has already attracted many researchers [4, 10, 11, 12]. Shannon's information theory has been proposed a) as a framework to analyze and understand the sonification field and b) as a tool that quantifies the information transmitted in auditory displays [10]. Entropy has been proposed as a sonification design tool [13, 14, 15, 16]. The distinction between the concepts of information and data related to sonification has already been studied from the viewpoint of philosophy and cognitive science [12]. More recent works deal with data interpretation and information extraction in sonification [4]. Despite the importance of these studies, the structural characteristics of information during the process of sonification have not been discussed.

Acknowledging that in the context of sonification further distinction regarding data and information transmission needs to be made [17, 18], in this work, it is argued that the resolution of this ongoing debate can be better addressed by describing sonification through entropy and information. In this paper, sonification is presented as a communication model for which the structure of its intermediate components is determined by the information flow from a source to a receiver. The concepts of data and information in the context of sonification are clearly distinguished and related to well-established sonification techniques. Finally, the arrangements of the components of the sonification model are described in terms of entropy.

2. ENGINEERING AND SEMANTIC ASPECTS OF INFORMATION

The focus in this information-based description of sonification is to provide a link between information and sonification. The approach presented in this paper interweaves information as contextualized by science, communication engineering, cybernetics, and systems theory. As information is related to uncertainty, acquiring a piece of information means obtaining knowledge for something which is previously not concretely known. Entropy was the first physical concept that was related to uncertainty and was linked after Maxwell's demon thought-experiment [19] with information for this exact reason. The term was introduced in the field of thermodynamics by Clausius and indicates the number of ways a system can arrange its components. It is a way to describe the possible configurations of a system. For example, a system comprised of an on/off button has two possible configurations.

In the engineering community Shannon's consideration of entropy and information, which led to the establishment of the field of Information Theory [20], is the common ground. Shannon connected information with uncertainty and proposed a mathematical formula quantifying information in bits. The less predictable the outcome of a procedure is the greater the obtained information becomes. For example, tossing a heavily biased towards heads coin (e.g., 99% probability to be heads and 1% to be tales, little uncertainty) is less informative than tossing a fair coin (50% probability to be heads and 50% to be tales, maximum uncertainty).

Although used for different purposes entropy and information for physics and for communication engineering are conceptually related terms. The number of ways the constituents of a system can be arranged is related to the possibility of each way to take place. A higher value of this number means lower possibility and therefore, higher uncertainty. In this work, the term entropy is used as a factor of possible ways a system can be arranged (entropy as freedom, instead of the common description which links entropy with disorder [21]).

Information Theory from an engineering point of view focuses on minimizing the risk of garbling a message when coding information. That is achieved by the design of communication systems that operate for every possible selection from the set of possible messages. However, the semantic aspects of communication are not relevant in the engineering problem [20]. In communication systems -sonification can be viewed as such system- the determination of the semantic question of what to send and to whom to send it to [22] is of great significance. A sound is considered to be meaningful when it carries information that can provoke changes in a receiver's mind-set. Meaningful sounds are either intentional (i.e., purposely engineered to perform as an information display) or incidental (i.e., non-engineered sounds that occur as a consequence of the operation of a system) [23]. Sonification, which is part of the former category, constructs intentional audio messages. A sonification system is well-designed when: a) the information constituents (data) are successfully transmitted (engineering problem) and b) the audio message is meaningful (semantics).

The General Definition of Information (GDI), treating data and information as reified entities and studying information in terms of *data + meaning* [24], provides a solid framework to study the informational aspects of sonification. According to GDI:

"σ is an instance of information, understood as semantic content, if and only if:

- (GDI.1) σ consists of one or more data;
- (GDI.2) the data in σ are well-formed;
- (GDI.3) the well-formed data in σ are meaningful. [25]

Information cannot be data-less and it consists of at least a single datum (GDI.1). A datum is the non-reducible lack of uniformity (e.g. a black dot against a white canvas) and it is materialized in the discrete state of a difference (Diaphoric Definition of Data DDD [25]). Data, considered as the units of information, are differences that can potentially provoke corresponding differences ("Information is a distinction that makes a difference" [22], "Information is a difference that makes a difference" [26]).

Data describing a system are potentially meaningful by being formed in clusters following the rules (syntax) of the system (GDI.2). Every organized form follows syntactic rules (e.g., a painting, a chess game, a company, a molecule, etc.), with the syntax determining the structure and architecture of the system. A message sent through a communication channel can be either meaningful or not judging by the delivered information to the receiver. [27]. The perception of information provides meaning to a message as information conveys meaning only if it can have an effect on the detecting entity and the data comply with the meanings (semantics) of the system [25] (GDI.3). In this work differences in every component of the sonification communication model that have an effect on the detecting component and cause correspondingly structural changes are inspected. As Reading argues: *Meaningful information can thus be defined as a pattern of organized matter or energy that is detected by an animate or manufactured receptor, which then triggers a change in the behavior, functioning, or structure of the detecting entity* [28]. The transmission of meaningful information is related to the propagation of organization [27]. The information content of an information-processing activity, such as sonification, is the guideline of how an organization propagates through the components of the information channel.

The digital communication engineering community uses binary digits (bits) to describe data that take their value depending on the answer: Yes/No. Information can be seen as queries + data [25], consistent with the GDI's scheme: *information = data + meaning* [24]. The semantic content of a message (its meaning) is found on the question asked (query) and portrays the informational value of the message. Shannon's Information Theory looks at the successful transmission of data within a communication channel without considering the significance of the question asked. In other words, for the Shannon's engineering perspective, every data are of equal importance, regardless of their semantic content - informational value. For example, the first bit of a two-bit message reporting a car accident, coming from the answer of the question "Are the passengers alive?" is far more important than the second one deriving from the question "Did the tiers go flat?". So, even the first bit carries a message of clearly a higher informational value than the second one, their successful transmission is of equal importance from the Shannon's engineering point of view. The length of a message (the number of bits it contains), depends on the number of queries asked to fully capture a phenomenon. This is equivalent to the data deficit of the informee regarding the observation of the phenomenon (e.g., before a coin is tossed the informee is in a state of data deficit of 1 bit).

The outcomes of this section are summarized in Table 1 which provides a set of descriptions and definitions of the key-concepts used to form our framework.

Table 1: A set of descriptions and definitions of the key-concepts used to form our framework.

Term / Concept	Description / Definition
Information	A physical quantity [8] that creates organized structures [9] Information = Data + Meaning [24] A difference that makes a difference [26]
Entropy	Indicates the number of ways a system can arrange its components (entropy as freedom [21])
Data	The units of information The non-reducible lack of uniformity Materialized in the discrete state of a difference (Diaphoric Definition of Data [25]) Differences that can potentially provoke corresponding differences
Meaning	Meaning = Information - Data [24] *"Meaningful information can be defined as a pattern of organized matter or energy that is detected by an animate or manufactured receptor, which then triggers a change in the behavior, functioning, or structure of the detecting entity."* [28] The transmission of meaningful information is related to the propagation of organization [27]

3. SONIFICATION COMMUNICATION MODEL

3.1. The description of a generic Sonification Communication Model

In this work, sonification is approached as the process that arranges information gathered from a phenomenon into organized patterns of sound. Sonification can be described as a communication channel from a source (the phenomenon) to a receiver (the listener) [2]. This is further developed by describing in a more elaborate manner the components of this communication model (i.e., the phenomenon, its numerical interpretation, the organized sound, and the listener). These intermediate components are treated as independent domains, where every single one of them constitutes a system. The organization of the components of each system depends on the information flow from the one end of the sonification communication model to the other. In this sense, information can be considered as a causal agent that provokes transformations within the components. In order to avoid information losses, the transformed components have to be structurally related. In the communication channel (consisting of components) the flow demands a representation that will allow the propagation from one component to another. MacKay defines representation as *any structure (pattern, picture, model) whether abstract or concrete, of which the features purport to symbolize or correspond in some sense with those of some other structure.* [22]

Between the phenomenon (source) and the listener (receiver) intermediate components (grey boxes, Figure 1) constitute the complete sonification communication model (1). The phenomenon (first component) is numerically represented via measurements (illustrated with a dotted background box, 1) by using measurement devices and stored in a storing device. This is a representational procedure, because it falls into the category of a structure the features of which correspond to those of some other structure [22].

The captured data are ordered in a specific meaningful way that illustrates certain characteristics of the phenomenon. The measured dataset (second component) consists of data (the constituents of information - GDI.1) that are not necessarily useful as a part of the sonification model. Data preparation is a mathematical procedure unveiling the information about the phenomenon (i.e., the meaningful differences that can cause corresponding differences [26]) and enables the feature extraction. This step involves several mechanisms, such as data reduction, mathematical transformations or event extraction (e.g., extrema) [29] and through which an informative dataset (third component) is formed. The informative dataset contains the data-relations that are potentially meaningful (GDI.2).

The informative dataset is mapped into sonification attributes according to the sonification algorithm which is a representational procedure because it falls into the same category as measurements. This second representational procedure forms the organized sound (fourth component), which is expected to carry the meaning to the listener (GDI.3).

In the final step, the playback system (illustrated with a chessboard background box) is a sound generating procedure materialized as an apparatus which is responsible for the generated audible sound (the sonification of the phenomenon) that reaches the listener.

The sonification communication model presented in this paper resembles the Shannon-Weaver model of communication, an important aspect of which is noise [19]. In the sonification communication model noise can appear in many forms; from technical aspects of the measurement instruments and the playback system to prior knowledge, understanding, and cultural aspects of the sonification designer and the listener, as well as of the designer behind the dataset.

The presentation of the sonification communication model concerns the one-way communication from the phenomenon to the listener. However, it could be argued that sonification must be interactive to be useful [30]. Interactivity, although not explicitly

Figure 1: A generic sonification communication model. The components of the model are illustrated as grey boxes. The representations of one domain into another are illustrated as dotted background boxes, whereas procedures (in this case mathematical and sound-generating procedures) as chessboard background boxes.

described, can be included by the model, since the listener can actively modify while listening all of the intermediate components of the model. Thus, the proposed sonification communication model is adjustable and able to describe interactive processes.

3.2. Designing a Sonification Algorithm

The meaningful information substrate (semantics) of every phenomenon, seen as a system, is independent of the informee. For example, an English menu is regarded as information even for a non-English speaking customer. In this context, a translation application can make the information accessible without affecting the semantics of the initial menu. The information of a system can be decoupled from its support and the semantic content can be interpreted in any different format and medium [25]. For example, the above menu can be analog or digital, displayed on a leaflet or a screen, translated in various languages, the ingredients can be written down or shown in pictures, etc. Sonification design aims to create an interface that makes the information of a phenomenon accessible to an informee through the medium of sound.

There are many studies focusing on how sound can carry meaning [31, 32, 33, 34, 35, 36]. In this work, an alternative approach is proposed, which highlights that meaning (related to the propagation of organization [27]) provokes the representation of a phenomenon into an organized sound. The organized sound should enable the perception of information. A sonification model is well designed when the representation is a structure-preserving one (i.e., it *preserves the most important elements, connections and relations such that sequences of actions and chains of reasoning in the target domain also make sense in the source (and vice versa)* [37]). Sonification is a human-oriented exercise and involves the process of listening (i.e., a higher-order function than passive hearing that actively requires intention and attention [38]) and the use of cognitive resources). Evidently, it fulfills its purpose only when it enables the listener to draw conclusions from the phenomenon. Therefore, the designer should take into account that the listener has a specific cultural background in terms of knowledge and preconceptions [39] and form the design choices correspondingly. A well-designed sonification algorithm ensures that the representation is both structure-preserving and interference-preserving [37, 40]. According to the GDI framework, the generated sound should be organized and well-formed (GDI.2) and potentially meaningful for the listener (GDI.3). For example, musical sonification as a conveyor of information is datable [12] since the purpose of musical composition (even if it is data-driven) is the creation of an aesthetically pleasing work and not of a mean enabling a better understanding of the underlying data driving the composition. Although it is data-controlled music [41] (i.e., structure-preserving, GDI.2 is fulfilled), it is not an interference-preserving procedure, since it targets mainly the artistic perspective rather than the transmission of information (GDI.3 is not fulfilled).

3.3. Sonification of data, data relations, or information?

In the sonification community, the distinction between the terms information and data is still not clear. This is justified because sonification primarily deals with phenomena the information of which can be straightforwardly translated into data, resulting in their interchangeable use [4]. The sonification algorithm, which is a part of the sonification communication model, uses a number of inputs (i.e., data) leading to the belief that the sonification is synonymous only with data sonification. Referring to sonification as a technique that uses data as input to generate sound signals [41] and stating that in sonification we listen to data in order to gather information [42] (related only to GDI.1) is a partial truth. The community sees that in some cases the sonifier's intent is the sonification of data relations (related to GDI.2) and not that of the raw data itself (related to GDI.1) [1]. For example, raw data from a GPS - tracking position device can only inform someone about the position of the object, whereas data relations from the same dataset can further inform someone about the movement of the object (e.g., speed, acceleration, elevation, etc.). In reality, information is structured data [27] and is embedded into data by constructing data relations (i.e., abstractions of, or from, the data [18]). Scaletti proposed a definition of sonification as *a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purposes of interpreting, understanding, or communication relations in the domain under study* [43]. Barrass further stretched the limits of this approach by directly referring to information instead of data relations [17]. Concluding this subsection, although *information can always be represented numerically and thus to be understood as data* [41] the sonification designer should rigorously distinguish which type of dataset (the measured or the informative) describes more accurately the phenomenon.

4. DO WE LISTEN TO DATA OR INFORMATION

When listeners receive the organized sound produced by a sonification procedure, do they listen to data or information? The answer to this question is that it depends on the designer's intention and whether the informational value of the representation of the phenomenon into sound is known before the procedure [18] (Figure 2). When it is, the designer's intention is to directly sonify this knowledge, i.e., information sonification based on the acoustic representation of data relations [18]. On the other hand, when the informational value of sonification is not known before the procedure, the designer's intention is to generate a sound that enables the listeners to explore the phenomenon (i.e., to determine the potential queries describing it) and acquire the information by themselves. This is the case of data sonification which is based on the acoustic representation of data [18].

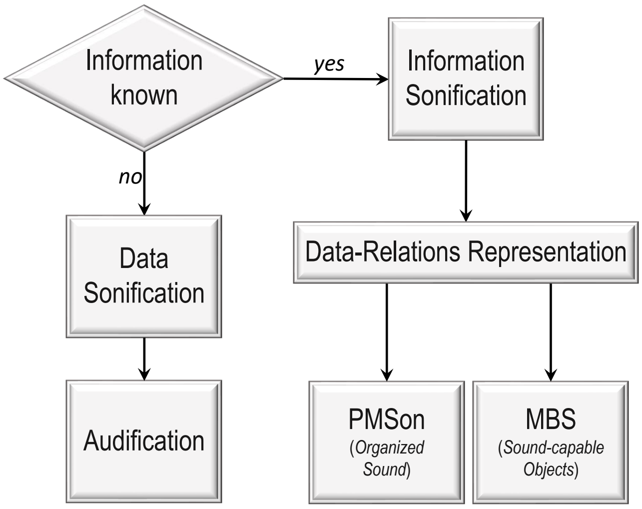

Figure 2: The sonification techniques related to data and information sonification. In the case of information sonification, the informational value of the representation of the phenomenon into sound is known before the procedure. This information is coded in data-relations which are represented into organized sound (PMSon) or into sound-capable objects (MBS). In the case of data sonification, the informational value is not known before the procedure and organized sound is the representation of raw data (Audification).

Audification is the sonification technique that a data waveform is directly translated into sound [36] and hence it is related to data sonification. This is a useful technique to explore phenomena the information of which is not known before the sonification procedure. In order for this technique to be fruitful, the listener should have access to the raw state of the measured dataset. The designer should therefore build a sonification communication model with minimum data transformations [44]. This is a direct representational scheme [35] described by a 0th-ordered mapping, i.e., sonifying to a stream of data directly as an audio signal [37]. Since there are no data relations to describe the phenomenon before the listening activity, the informative dataset is not a component of the audification communication model. The transformations taking place are signal conditioning transformations [44]. Hence, in audification, the listener listens to data (i.e., the organized sound is the representation of the measured dataset). Through the organized sound, the GDI.1-related raw data of the phenomenon are accessible to the listener. Subsequently, the listener is expected to discover the data-relations (the syntax, related to GDI.2) in order to extract the meaningful information (related to GDI.3).

Differently, when the informational value of the phenomenon is known before the sonification procedure, information is expressed in data relations (related to GDI.2) and the designer forms the informative dataset. This dataset becomes the input of the sonification algorithm. At this point, it is the GDI.2-related data relations that become accessible to the listener. Subsequently, the listener is expected to extract the meaningful information (related to GDI.3). Information sonification includes primarily two techniques, the Parameter Mapping Sonification (PMSon) and the Model Based Sonification (MBS), which differ on the informative dataset represented domain. In PMSon the acoustic attributes of events are obtained by mapping from data attribute values [45]. Therefore, the informative dataset represented domain is the organized sound. This technique is based on the first or higher-order mappings. In the case of the first order mappings, the parameters of a synthesis model are modulated by the use of a stream of data, whereas in the case of higher-order mappings, data determine the structure of the synthesis model or modulate subaudio control signals that control the parameters of the audible signal [37]. In MBS, the informative dataset represented domain is a sound-capable object. This representation determines the architecture of a dynamic and interactive model [46].

The common ground of these techniques (Audification, PMSon, and MBS) is that mappings (representations) are taking place since *something is represented in a form external to itself* [47]. In Audification data determines the sound signal, in PMSon the features of sound and in MBS the architecture of a dynamic model for sound generation [46].

5. THE ORGANIZATIONAL POSSIBILITIES OF THE SONIFICATION COMMUNICATION MODEL COMPONENTS

In this section, it is demonstrated that the propagation of organization in the sonification communication model can be expressed as entropy. Entropy is a numerical indication of the number of microstates (i.e., possible arrangements of the constituents of a system) that correspond to a certain macrostate (i.e., the state of a system with certain properties) and has already been used in audio engineering applications (e.g., [48]). Therefore, information can be expressed as the causal agent of the possible arrangements and for a goal-seeking system, it is coded variety [49]. This leads to the simile *entropy as freedom* [21]. A significant task in this kind of sonification design is to determine the variety of the possible arrangements of the components of the communication model (i.e., the entropy expressed in the length in bits).

The variety of possible arrangements is linked with sonification functions. The simplest function of sonification, which can be expressed in terms of entropy, is the alarm system. It is considered to be the simplest function because the phenomenon is represented as a system of only two states (event is true or false, data deficit of 1 bit). Let's consider a fire alarm system detecting smoke. The smoke detector, which in this case is the measurement device, records the amount of smoke present in the room (measured dataset). However, in this system, the acoustic representation of the amount of smoke is not relevant. To avoid delivering unnecessary information in such binary systems, the event is true or false when the measured value is above or below a certain threshold, respectively. These two possible stages consist of the informative dataset corresponding to two possible arrangements of the organized sound. The listener is expected to link these two stages of organized sound with the existence or absence of fire (inferencepreservation).

Let us now consider that the detector measures and gives information about the amount of oxygen available in the room as well (the informee is in a state of data deficit of more than 1 bit). In this case, the aforementioned alarm system (one-bit audio message) would fail to sonify the phenomenon. More complicated functions of sonification (e.g., status, process, and monitoring messages and data exploration [2, 36, 50]) transmit more information (the informee is in a state of more than one-bit data deficit) and require correspondingly more organizational possibilities (higher entropy).

With this example, the reader can evidently see why propagation of organization is possible only if the components of the sonification communication model have at least as many organizational possibilities as the phenomenon. The number of the organizational possibilities of each component depends on the data deficit of the informee regarding the phenomenon. If the informee is in a state of n-bit data deficit, then the propagation of organization demands at least n-bit components to achieve structure-preservation, in which case, information loss is possible.

6. CONCLUSIONS

This paper attempts to describe a new approach, based on the structural aspects of information, to illustrate how sonification enables the listener to explore and/or get informed about a phenomenon. This work aims to contribute towards the resolution of design issues that arise from the ambiguity regarding the use of the terms data and information, by clarifying them within the context of sonification. This approach is expected to help designers choose more robustly the corresponding sonification technique and avoid information losses, resulting in a more efficient representation of a phenomenon into organized sound. Moreover, the 4th industrial revolution brings new engineering and philosophical challenges. To be able to correspond to these challenges, the field of sonification needs to update its directions. As part of this process, this informational-based description of sonification will be further developed in order to study aspects of the sonification of big and complex data. Additional next steps include the modification of the model in order to further consider 1) aspects of interactive sonification, 2) user-centered design principles, particularly, regarding the listening context, and 3) the two-way information/data flow within the communication model. Last, after Xenakis, several composers and media artists develop algorithms that translate physical, social, and other phenomena to music. By collaborating with scientists, the artists study the phenomenon to unveil repeated structural patterns. Thus, by adopting outcomes of the evolutionary theory and computational evolution, the further development of the approach presented in this paper is expected to be proved beneficial for such data-driven algorithmic compositions. In particular, it can help composers determine which dataset (the measured or the informative) better describes the studied aspects of the phenomenon and can drive the music composition.

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