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A Design Model for Systemic Sonification

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Systemic sonification is a recent proposal for sonification design that offers interactive sonic fields. Inspired by living systems theory, it is formed by a community of sound beings that, as perceived sonic entities, respond to and evolve through human interaction. However, this abstract conceptualization lacked a design model for exploring its design space. The authors present a six-stage design model for envisioning interactive sonic fields, which emerge from the interplay between sound beings and human participants. This model is grounded on eight key concepts (Listener, Translator, Signifier Generator, Composer, Performer, Emitter and Collector), modeling agencies that define a design space for structured yet malleable sonic explorations. Two proofs-of-concept illustrate this model in practice to generate interactive system designs, ranging from objective mappings to subjective perceptions. A Pluralistic Walkthrough was conducted with two data domain specialists, aiming to gain insights on the prototype and discuss design variations based on the model. The authors reflect on the systemic model as a design tool, discussing 1) its generativity to create novel design spaces for sonification and 2) the interaction opportunities that emerge to explore subjective action-perception with sound beings.

0 INTRODUCTION

With the broad definition of communicating information through sound, sonification has been the subject of conceptualization, development, and research for more than 30 years [1], exploring human perceptual abilities to understand data relationships from acoustic signals. Despite the richness of exploration within sound perception, composition, and interaction, the field has been at a standstill regarding global adoption and materialization. John Neuhoff, one of the founders of the field, has recently reflected on these challenges [2, 3], listing the reasons as a combination of 1) the subjective nature of sound, 2) perceptual and listening differences between individuals, 3) the precision of vision compared with audition, 4) musical influence of the sonification designers and the users' backgrounds, and the 5) interdisciplinary nature of the research field. The multitude of dimensions to be worked upon establishes the ongoing difficulties of the field as a wider research interest.

A recent proposal that embraces multidisciplinarity and the user's active participation in the sonification experience is the *systemic sonification* [4], grounded on the concept of a sonification as a living system. Regarded as a "dynamic, ever-evolving system that actively responds to changes in its environment" [4], a systemic sonification embraces human participation as the main interactive force in guiding the experience. These interactions take place between the participants and the main entities of a systemic sonification: the *sound beings*. The way they react and evolve in response to the participant's actions compose what the authors called *sonic dialogues*, the paths from which multiple interaction journeys arise. To create them, alternative designs are needed for designing interaction spaces that foster "unique experiences to arise for each human" [4]. The authors propose there is an inherent generativity in the sound beings, through an adaptive structure that shapes mutable sonic forms, which, in turn, invite varied explorations.

Although the systemic sonification has been introduced as a new approach to sonification design, there is not yet a design model that guides the design space for the conception and implementation of systemic sonifications. With this paper, the authors present the design of a systemic sonification model, grounded on interactive sonic fields with sound beings, which become central pieces of this design approach. The authors begin by presenting a thorough definition of the sound being concept and its main characteristics. The authors present a six-stage model for designing systemic sonifications, from which the concept of the sound being emerges as the ultimate manifestation of the interactive experience with human participants. Its manifestation is grounded on eight design concepts (Listener, Transla-

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tor, Signifier, Generator, Composer, Performer, Emitter, and Collector) that, as modular system pieces with distinct responsibilities and shared goals, architect interactive system designs.

The authors demonstrate the systemic model through two exploratory proofs-of-concept: one as a play experience and the other as an interactive sonic experience to explore neuroscience data. For the second exercise, a Pluralistic Walkthrough was conducted with two data domain experts to gain insights on the developed prototype and discuss the design opportunities based on the systemic model.

The main contribution is a design model for the systemic approach, grounded on eight key concepts and two proof-of-concept prototypes that demonstrate its applicability. The authors also reflect on how the model serves as a design guide for the development and discussion of the systemic approach, offering generative and interactive spaces for data interpretation and exploration.

The remainder of this paper is structured as follows. SEC. 1 comprises a review on sonification in human–computer interaction, presenting the systemic approach and the main concept of the sound being. SEC. 2 presents a six-stage model for systemic sonification, characterizing the purpose and tasks within each stage, grounded on eight key design concepts. SEC. 3 presents two exploratory proofs-of-concept that demonstrate the systemic model in practice. SEC. 4 describes the Pluralistic Walkthrough conducted with two experts, discussing the insights gained and the subsequent design improvements. SEC. 5 reflects on the design implications of the systemic model, the multiple dialogues it generates between the participants, the designers, and the data specialists, and concludes on how it offers a novel design space for sonification design that may even surpass the sonification field.

1 SONIFICATION AND INTERACTION

Hunt and Hermann proposed the concept of "Interactive Sonification," refocusing the design goal on how “humans interact with a system that transforms data into sound” [5] through manipulating data-to-sound transformations in real-time. This perspective takes the human to the center of the process, focusing on designing systems that encompass the user’s actions and adapt to the user’s needs and interests. The authors distinguish themselves from interactive sonifications being seen as just musical instruments: more than their *expression* purpose of translating gestures into sound, interactive sonifications also aim at *data analysis*.

The last decade brought alternative experimentations on how to embrace a wider interpretation of sonifications. The discussion of boundaries between music and sonification [6, 7], exploring a “palette of properties of sound and mapping properties” [8], has been regarded both as a positive connection that makes the auditory result more “listenable, attractive and engaging” [9], but also as one that blurs the field’s limits and, consequently, its widespread adoption [3]. User-centered proposals also include the AeSon interface, which allows real-time customization of sound mapping properties [10]. Embodied interaction was more recently explored in Roddy’s embodied cognitive approach to designing sonifications [11], applying perceptual patterns of everyday life that carry conceptual meaning, and also in the *Springboard* experience [12], in a room-sized environment that triggered audiovisual cues through body movement. An interesting conclusion drawn was that the users usually perceived auditory fluctuations “as a duality between balance vs. out-of-balance” [12], through the idea of a “normal state” that was halted. This disruption can be associated with the Model-Based Sonification technique proposed by Hermann, which applies dynamic models that “mathematically describe the evolution of a system in time” [13], offering interaction possibilities by exciting the system. A recent reflection defended the role of the user and embodied cognition as a *subject-position*, coupling data transformations to the user’s embodied associations as the perceiver of sonification. Sonification aesthetics thus become an “an experiential, ecological or perception-action aesthetic” [14].

However, sonification remained bound to a functional perspective, translating what is considered the “pure meaning of data” [4]. Integrating an active user that can manipulate the sonification system is still largely constrained by the designer’s choices. How could we expand sonification design to be more malleable to user exploration, moving from the designer as the expert and sole responsible, to each participant becoming a co-designer of the experience?

1.1 The Systemic Approach

A recent proposal has approached sonification as a living system [4], embodying concepts from systems theory and systemism [15, 16], post-phenomenology and embodied interaction [17, 18], as well as soundscape studies [19, 20]. The novelty of the systemic sonification proposal is the multitude of interaction paths that each participant may tread while interacting with the main entity of the systemic setting: the sound beings (explained in the next section).

The systemic thinking provides a conceptual grounding for an expanded design space that sees sonification as a multistable phenomenon [21], that is, one space with multiple facets of exploration that lead to varied meaning-making paths. By proposing a multistable interaction dialogue between participants and sound beings, it is a new approach regarding sonification aesthetics, transformed into “contextual, unique and mutable sound narratives that unfold for and with each participant context” [21].

Meaning becomes multifaceted: by elevating Interactive Sonifications to be unique for each participant, we move beyond the designer’s perspective as the right, expert view over data to embrace a multitude of scenarios and interpretative forms for interacting with sound. To this end, the authors presented a sound-only, touch-based sonification of consumption data that illustrates the systemic design [22].

1.2 Concept of Sound Being

The *sound being* is one of the main concepts within the systemic sonification design space. As the elemental entity of its community, the sound being was originally described as “an auditory element whose behavior evolves

with external interactions, either from other sound beings or from human intervention" [22]. According to the authors, the mutable structure, communication flow, and behavior of the sound beings are the driving force of the experience, offering interactive exchanges with human participants.

Schafer distinguishes a *sound object* from a *sound event*, the first as an "object for human perception" that exists beyond referential standpoints as "a phenomenological sound formation" [20], and the second as a symbolic occurrence, contextualized in a given space and time. The sound being rises in the systemic setting as an entity that lives, reacts, and interacts with their surroundings, learning through the memory of previous interactions and evolving in response to changes in its context. Embedding Merleau Ponty's phenomenological view, humans are a part of the world: we exist prior to every conscious act as a *being-in-the-world* [18, 21], which is then shaped by a bodily, cultural and social presence; and it is through that *being* that we relate to the world. The sound being and the participant thus shape a relationship of meaning through interaction, from which the sound "being" emerges.

There is a systemic reinterpretation of active listening: on the system side, through a flexible structure that adapts itself and its behavioral mechanisms depending on human input, and on the human side, through each action that expands the perceived possibilities within the interaction space, with each new gained perception guiding subsequent actions. These exchanges translate a phenomenological grounding of "perception requires action" [17, 18] or "action-perception loops mediated by sound" [23]. Ultimately, as understood by [4], "perception IS action," as it is through these iterative exchanges (with the sound beings) that the meaning-making processes unfold.

The sound being, as an adaptable entity, is not precoded within the system: it is a sonic emanation of the system, perceived by the human participants. The interactive narrative with the sound beings unfolds as follows: 1) a designed system offers an interactive sonic field for exploration; 2) participants there encounter sonic appearances as emanations of the system; and 3) coherent appearances across interactions are perceived as sound beings with recognizable identities. As their behavior evolves with each interaction, meaning is iteratively formed, adapting the perspectives of each participant as well. The sound beings, how their language is composed, and how they evolve over time define the design space and challenges of the systemic approach.

2 SYSTEMIC DESIGN SPACE

Transitioning for a systemic thinking is grounded on the concept of the sound being, which becomes a conceptual infrastructure for the design of interactive systems. Its sonic response and perceived behavior may be influenced by varied sources, from human interaction, time-based events, place-based inputs, data parameters to composition rules and others. The sound being, as a sonic manifestation of the systemic setting, can be designed from a set of cooperative roles. This modularity stands on a variety of design focuses, translating different responsibilities to agencies, which compose each system stage. How these roles are processed and communicate with each other feeds the participant's perception within the sonic field.

The concept of computational and coordinated agent roles comes from the Multi-Agent Systems (MAS) [24] paradigm, which inspired us in the conception of the systemic model. It is grounded on the coordination and dialogue between heterogeneous agents with distinct allocated tasks. There is a vast body of knowledge on how to solve complex computing problems with task parallelism techniques, whose specificities are outside the scope of this paper. However, there is a characterization of *agent* that we found particularly helpful, which regards it as "an encapsulated computational system that is situated in some environment and this is capable of flexible, autonomous action in that environment in order to meet its design objective" [24]. An agent is defined with four dimensions, as an *entity* placed in a particular *environment* within the system, sensing different *parameters* that influence the decision-making process, and then performing the necessary *actions*. The entity encapsulates the type of the agent, which translates its design objective. The environment is what surrounds the system, from which each agent receives the necessary information to perform its allocated tasks, which, in turn, cause some kind of change to its surroundings.

The sound being, as an interactive entity, encompasses a variety of tasks, cooperating through internal dialogues, translating external stimuli, transforming data sources into behavioral influences, and composing a sonic response based on a structural sonic language. The design complexity of the sound being comes from sequential inner tasks and decision-making processes that define its social processes. We took this notion of multi-agent structure, with entities responsible for distinct design tasks, to deconstruct the sound being and study what a systemic model entails.

2.1 Eight Key Design Concepts

The proposed model is grounded on eight concepts. Their roles entail distinct design focuses and potential functionalities within a system, becoming modular pieces to be combined depending on the design goal. As system agents, their interaction and collaboration compose the behavior of the system, becoming low-level concepts for the designer to model a system that synthesizes interactive manifestations of sound beings. The eight roles are now summarized and further explained alongside the model:

1. **The Listener**: placed at the border of the system, its main role is to listen to external stimuli. It may be a *data listener*, attentive to data sources, or an *action listener* that listens to the participants' interactions.
2. **The Translator**: has the main task of processing raw input data into coded interaction events, which trigger new processing cycles within the system.
3. **The Signifier**: is responsible for processing the translated external events through a pipeline of event-decoding functions, grounded on the system's own language and interpretation model. It may pro-

cess data-related functions as a *data signifier* or interaction-related events as an *action signifier*.

4. **The Generator**: its main role is to generate elemental sonic pieces of design to be combined, recombined, and merged during the interaction process.
5. **The Composer**: is the main orchestrator of the experience, responsible for combining generated sonic elements into a final score.
6. **The Performer**: has the role of expressing the final composition, giving a corporeal form to the system's design choices.
7. **The Emitter**: responsible for transmitting the final sonic output in the interactive sonic field.
8. **The Collector**: is a shared memory that saves previous exchanges. Retaking a concept regarding agent communication within a MAS [24], a *collector* resembles a blackboard, for every agent in the system to save information and read stored messages.

2.2 Six-Stage Structure

With the systemic model inspired by MAS, agents become modular components from which the system is built and configured over time. Their behavior determines how the system is permeable to outside influences, shaping the dynamic nature of the system to devise sonic interaction fields.

We will now present our proposal of a design model for systemic sonification (Fig. 1), in an interactive loop that comprises six main stages. The model intentionally encompasses the interaction space as the first stage, where the direct interaction with the participants take place, and whose stimuli feed the system in return.

2.2.1 Interactive Sonic Field

The first stage is where the main interaction takes place, with humans as active participants encountering the sound beings. In the systemic setting, the sound beings are the final manifestation of the collaboration between the system agents, and the only in direct contact with humans: as interactive entities present in the interaction field, they represent the final auditory result in the way they move, sound, and respond. Their iterative and interactive exchanges form the arcs of action–perception [18, 21]: each response from a sound being is perceived, questioning what it meant, what triggered it, what changed, thus grounding the next significant action to perform. The sound beings gain their phenomenological form in the sonic field, as sonic appearances to interact with, influence, and be influenced by.

2.2.2 Event Recognition

We encounter the first agent at the frontier between the first and second stages: the *listener*. It is a passive agent, responsible for listening to external stimuli. In this stage, *action listeners* receive input from human participants present in the sonic field, listening attentively to their interactions.

The purpose of this second stage is to receive stimuli from human presence, translating and encoding them into system events. Event encoding can include sets of time-based or place-based events, representing physical gestures or movements from the participants. *Translators* are thus the agents responsible for receiving external raw input from the *listeners* and producing a set of events.

2.2.3 Event Processing

After the *event recognition*, each received event can be processed by a specific function within the system. External stimuli are encoded as events, carrying intentions and meanings to be interpreted by the system. *Event processing* is the duty of the *signifiers*, a term inspired by semiotics. *Action signifiers* are here responsible for interpreting action events and form a meaning for the system to process.

In this stage, we also process events that do not derive from external inputs, but from internal, ongoing processes, such as clock-based events (e.g., that periodically activate a function or send messages to specific agents) or preserved memory of previous events, stored by *collectors* or distributed individually in each *signifier*.

2.2.4 Data Processing

The fourth stage encompasses the first step of what is usually defined as the main purpose of a sonification: to translate data into sound, transforming the relations between data variables into "perceived relations in an acoustic signal for (...) facilitating communication or interpretation" [1]. Data are the main ingredients of sonifications, intended to be transformed into sound to be listened to, experienced, and, in some way, apprehended.

A preprocessing stage is needed to prepare data to be transformed into sound, which may involve filtering, combining, sorting, aggregating, and other operations that process the intended dataset. Data sources are the external stimuli that enter this stage through *data listeners*, placed at the system's border receiving data streams. These are then processed by *data signifiers*, the main agents in this stage whose functions include all data-handling operations to filter, analyze, and prepare incoming data messages to be sonified. From accumulators, pattern recognizers, differentiators, or filters, these *signifiers* can be subdivided into specialized agents, each one responsible for a single type of data handling function. A continuous stream of data operations may also demand memory of processed data characteristics, either within each specialized agent, or with *collectors*, which save processed aspects of data patterns and singularities of a given dataset.

It should be noted that *data processing* is only necessary when working with external data sources. Working with data is a particular form of auditory interaction, which becomes an additional influence over the system's behavior and an external stimuli, similar to human presence. It is thus a stage particular to the field of sonifications and data-focused experiences. We reach the end of this stage in our model with a set of interpreted events (encoded interactions or processed data) that will now be transformed into sound.

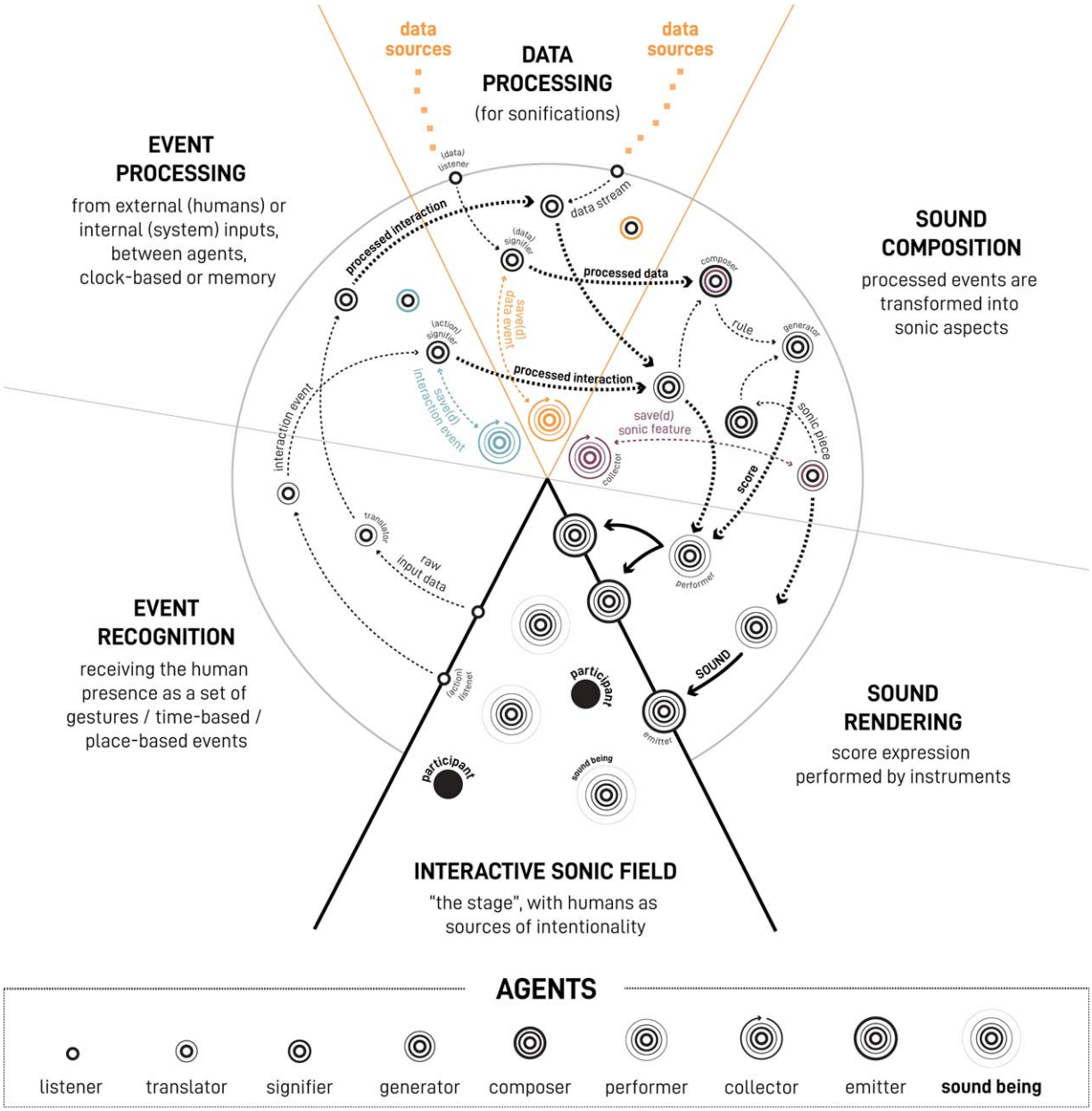


Fig. 1. Model for Systemic Sonification.

2.2.5 Sound Composition

The fifth stage of this model is where sound creation takes place: processed events are transformed into scores, as pieces of sonic elements that compose the sonic response of the sound beings. For creating what we may describe as *sonic dialogues*, we need to think about how sound, either organized into a musical form or not, can be deconstructed into sets of combinatorial sound characteristics. These blocks of sound are inspired by Schaeffer's notion of *musical phoneme* [25] and the relationship between language and music. He highlighted two musical features, pitch and duration, which define the "letters" of musical phonemes. These letters, when combined, create syllables that build words, the *leitmotivs*, which are short sound fragments that become auditory structures of meaning and characteristic of a given piece. Leitmotivs provide, recurrently and through variations and combinations, the musical identity of a piece.

We assume that the elements of leitmotivs can be dynamically generated, either from internal, predefined rules, but also from interpreted signs that originate from the external world. The *signifiers* give elements to the *generators*, agents responsible for receiving these inputs and transforming them into sound parameters. Each *generator* can build on different sound characteristics (notes, breaks, rhythms, intensity, recordings), with the *composers* reuniting them in a score to be played. Multiple *generators* can be combined by multiple *composers*, as we might also have *composers* specialized in different sound features: one might be focused on coordinating melodic choices, another on timbral combination, another on synchronicity (or asynchronicity, seeking disruption), and yet another on rhythmic patterns.

Each *composer* can feed itself from previous individual choices, from a general musical memory that establishes a musical identity, from collected data features, human-triggered events, or other internal processes. All of these sources can work together to generate sound blocks and compose a full, unifying score to be experienced.

2.2.6 Sound Rendering

The sixth and final stage of the systemic model shapes the final auditory output to be transmitted in the sonic field. This is the stage of the sound expression where the composed scores are played by a set of *performers*, playing the composition through a set of instruments. The term "instruments" does not necessarily translate the sound of an instrument *per se*, as a guitar or a piano, but the moment when *sound objects* gain a corporeal sonic form through a timbric definition. They also gain a referential standpoint, “both materially and mentally” [25], as individual entities to interact with. Each timbral feature chosen can be seen as a *performer* within the systemic setting.

The expressiveness of *performers* is translated into the final auditory result, emanating across the field through the last form of agents within this model: the *emitters*, placed at the borders between the fifth and sixth stages to symbolize the channels through which sound is rendered.

The cycle closes by returning to the interactive sonic field. The expressiveness of *performers* becomes a contextual phenomenon, in sequential *sound events* [20], that occur with the ultimate manifestation: the sound beings. They represent the sonic manifestation of the system through the perception of each participant. The sound beings are, simultaneously, the concretization of the system as a sonic manifestation and its abstract understanding by each human. Ultimately, this duality creates the emergent sonic dialogues between the participants and the system, which rise through their interaction with the sound beings in the interactive sonic field.

The proposed model for systemic sonification embodies the systemic approach through a coordinated process flow, whose constituent agents collaborate to perform the assigned responsibilities. The concept of sound being allows for multiple design spaces to unfold. As a sound or sonification designer, when devising the roles of each agent, one can consider the final sound being manifestation as a recognizable sonic entity, interactive and of evolving behavior. As such, one does not design for a discrete interaction [26] but for a dynamic field that embraces the perceptive multistability of sound interaction phenomena [21].

3 IMPLEMENTING THE SYSTEMIC MODEL

The systemic model intends to offer a novel design space for sonification design and the conception of interactive experiences. To demonstrate its generativity in practice, the authors now present two exploratory, proof-of-concept exercises, exemplifying the diversity of design explorations that arise when drawing on the systemic model.

The first exercise is a conscious deviation from the classic sonification goal, without an initial data source: interaction itself is sonified in the process, with the systemic sonification translating a sonification of its own experience. A playful scenario was embraced, as a first exploration of how one could design the sound beings focused on engaging the player, applying the model to understand how they were perceived by the participants. This first exercise was a key piece in the process of exploring interaction opportunities within the systemic setting.

For the second exercise, an interactive sonic field of neuronal activity was designed, using a dataset from a neuroscience study [27]. Encompassing all the stages of the model, the authors grew from what was learned in the first stage regarding the interaction space to explore how it could be combined to gain varied perspectives over the data space.

Both exercises were designed as near sound-only experiences, with a cursor as the only visible element that represents the user’s position and direction. The experimental setup consisted of one laptop, with the respective touchpad and keyboard as the main interaction inputs, and a pair of headphones. Technically, implementation is achieved through the real-time interoperation of two processes: a Processing sketch (Java-based programming language) as the main controller and interface, responsible for event and data processing, which are sent to Max to generate and compose the corresponding MIDI. The MIDI values are sent to a series of VST plugins[1] that produce the final auditory output. In these versions, a stereo setting was used for a simplified spatialization, based on the cursor’s direction and position.

The sound beings, as invisible entities, move randomly across the field. To design their sonic language, a previous developed Max system was adapted [28], structured on melodic features such as mode, key, and octave to define the scale of the leitmotiv. The notes of the leitmotiv (with an initial size between 1 and 3 notes) are chosen randomly: melodically from a melodic scale and rhythmically from five rhythmic figures (from whole to eighth notes). The leitmotivs for each sound being are played in loop.

The six stages are illustrated in Fig. 2: on the left, in the Processing environment, there is the main *interactive sonic field*, the *event recognition* and *event processing*, as well as the *data processing*; on the right, in the Max environment, there are all tasks involving *sound composition* and *sound rendering*.

3.1 Playing With Sound Beings

The first experience was driven by one question: “how would you play with a friend that you cannot see, you can only listen to?” Focused on designing the sound being as a responsive entity through musical dynamics, it provided the opportunity to discover the roles and key concepts in the systemic design. The authors conceived two sound beings with polarized personalities, based on two characters from our childhood universe [29]: Bert and Ernie. The first as

[1] https://labs.spitfireaudio.com.

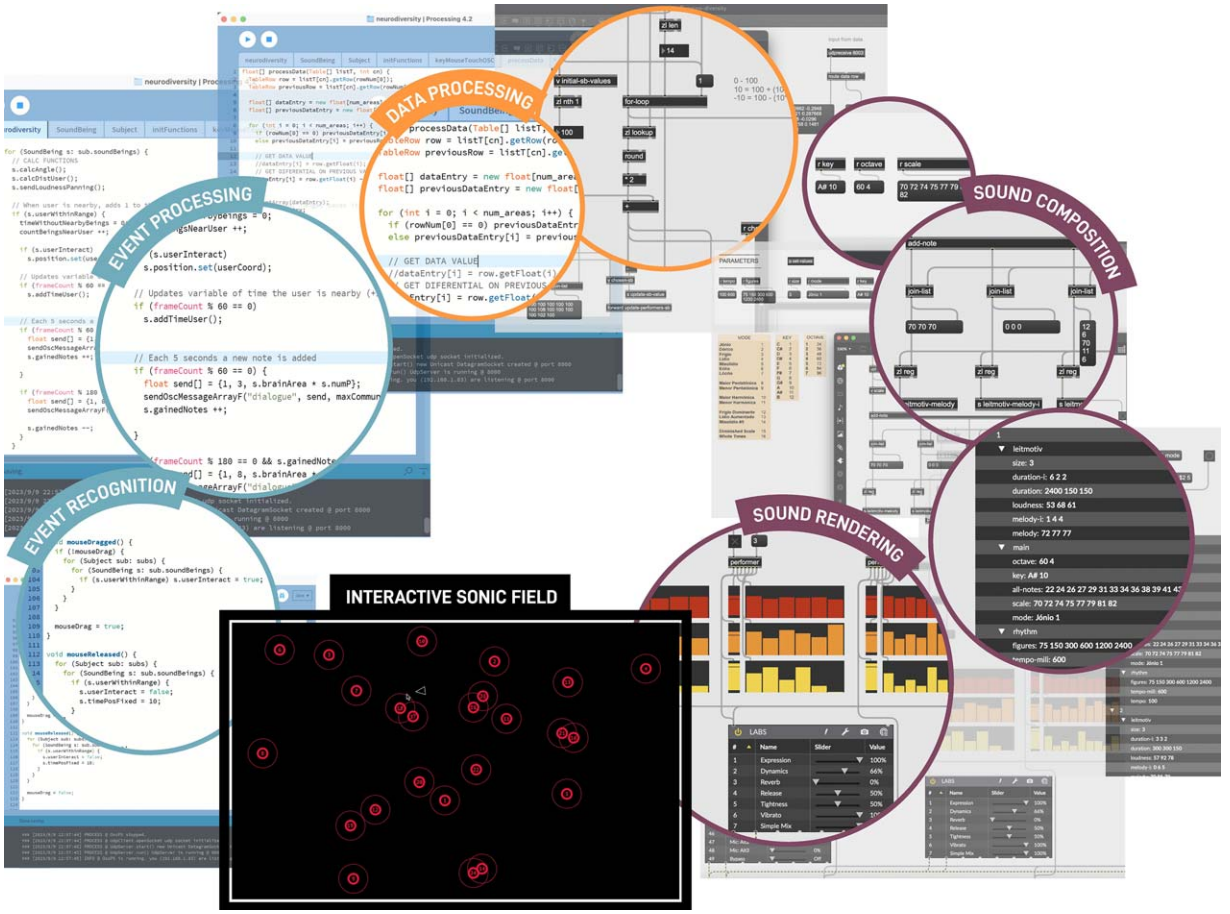


Fig. 2. Technical Implementation of the Systemic Model

an introvert, who tends to avoid social exchanges, and the second as an extroverted, social being. Their evolving sonic responses were designed with distinct rules to grasp how the players perceived them and their ongoing interaction as "playing *with* sound beings or playing *them*" [30], as if they were musical instruments. A video of this experience is available online.[2]

Although this exercise was published as a play experience [30], the model can inform us about its design space and how the agent concepts could be designed for user exploration. We can characterize the agents within each stage:

1. **Interactive Sonic Field**: two sound beings roamed across the field, Bert and Ernie, hidden from sight, waiting to be encountered.
2. **Event Recognition**: *action listeners* are implemented as Processing functions, which track interaction inputs to be decoded by the *translators*. These translate the participants' movement and key inputs, namely from 1 to 9, aiming at triggering sounds of an hypothetical dialogue with the sound beings.
3. **Event Processing**: the relationship between time and presence was the conceptual guide for interaction, with the presence of each participant near the sound beings implying a sense of interest. *Action signifiers* understand the time spent near each one as a calculated metric of attention. They are also attentive to the signs that arrive from key inputs, which trigger different musical responses from the *generators* and *composers* depending on the key pressed.
4. **Data Processing**: this stage, as an exercise designed without external data inputs, was not explored.
5. **Sound Composition**: Bert and Ernie's musical identities are grounded on distinct musical structures. Bert's *generators* limit the initial leitmotiv to a single, low-key note, while Ernie's may vary (randomly) between one to three notes in a higher octave. We set a melody *composer*, responsible for adding notes a) to Ernie when it faces a participant, b) to Bert and Ernie when they are both together, and c) when the three meet (Bert, Ernie, and the participant), thus sonifying a metric of attention.
   A *composer* is also assigned to increase Bert's octave when it faces the participant alone. In this situation, a rhythm *composer* is responsible for increasing Bert's tempo as well. When both sound beings are together, we have a *consonance composer* responsible for tuning their tempos and also for communicating with the *melody composer* to add a specific note to them both when a number key input is detected (elaborating the sound beings' expression). When

[2]https://vimeo.com/732106185.

the participant moves away after an encounter, another *melody composer* is responsible for gradually returning the leitmotivs of both sound beings to their original state by removing the last notes added.

6. **Sound Rendering**: the spatial presence of the sound beings within the soundscape is defined by the *performers*, which determine the values of loudness and panning in the Max environment, according to the participant's position and orientation. The *emitters* define the channels through which the sonic dialogues are performed, namely 1 and 2, outputting the final soundscape. In this experiment, channels 1 and 2 were mixed to achieve a stereo output.

Looking at this exercise through the systemic lens gives an overview of how the model could be applied. Regarded as a sonification of play interaction also enabled the authors to study how the agent roles could be defined and how each agency contributed to a working prototype using the available tools (Processing and Max). This proof-of-concept also enabled the authors to understand how cooperating agents could be structured to design the interactive experience.

3.2 Interacting With Data

Although the first experience was mostly an exploration of interaction within the sonic field, the second exploratory exercise is the main proof-of-concept of a systemic sonification experience, grounded on the proposed systemic model. The dataset was collected from cognitive task experiments performed with neurodiverse populations [27], comprising cognitive function activity data streams from 24 participants: a clinic group, with 10 individuals with high-functioning Autism Spectrum Disorder (ASD), and a control group, with 14 individuals with typical neurodevelopment (TD). Data were collected using a "novel task-based fMRI virtual-reality task" [27] named EcoSupermarketX, intended to evaluate differences in the social cognition and Executive Functioning (EF) capacities of the participants. Through the Functional Magnetic Resonance Imaging (fMRI) data, seven brain regions were measured (Table 1) while performing the intended tasks.

Table 1. Measured Brodmann's areas (and cognitive functions)

Parahippocampal Gyrus (Right)	BA19	- Scene recognition, spatial navigation, and memory encoding and retrieval (known to be a strength in of the cognitive profile of individuals with ASD)
Parahippocampal Gyrus (Left)	BA19	
Ventromedial Prefrontal Cortex	BA10	- Emotion regulation - Social behaviour - Decision making
Middle Frontal Gyrus	BA8	- Decision making - Working memory, episodic memory and multiple-task coordination
Middle Frontal Gyrus	BA10	
Cingulate Gyrus	BA24	- Processing emotions and behaviour regulation - Motor control and cognition formation, especially memory
Temporal Parietal Junction (TPJ)	BA22	- Shift attention to unexpected stimuli (reorienting of attention) - Reasoning of other's beliefs, intentions, and desires theory of mind

The systemic sonification model was applied as a design tool to conceive and implement the interactive prototype. The retrieved patterns of activation of cognitive functions in daily life "provide a circuit-level signature of neural diversity in ASD" [27], which served as a design motto for this experiment. The authors first decided the time-structured feature of the dataset as what temporally drives the experience, processing one timepoint for each tempo beat. The principles for sound composition were similar to the first exercise, assuming a leitmotiv structure to build the musical dialogues. Two questions guided their design: 1) what defines or influences the initial leitmotivs, and 2) what are their rules of evolution?

The system initializes with all the sound beings structured by the same rules, with the external influences (from the environment and from data) influencing their evolving compositions. Differences amongst individuals would then gradually appear during interaction, promoting the discovery of an emergent neurodiversity in the dataset. A video of this experience is available online.[3]

This exercise aimed for interactive exploration and comparison between groups (experimental and control), enabling opportunities to listen to and recognize patterns and differences within the dataset. With the systemic model, two parallel design alternatives will be presented next, describing how the agents within each stage could be designed to achieve different explorations and demonstrating the generativity of the systemic model as an ideation tool.

3.2.1 Interactive Sonic Field

Departing from two individuals (one from the experimental group, another from the control group), 14 sound beings roam the sonic field, seven from one individual's brain regions data streams, seven from the other. For this design, a flocking behavior was applied, simulating the group behavior of birds based on forces of separation, alignment, and cohesion around a center, to offer a sense of union and aggregate representing each individual.

Another design alternative populates the sonic field with 24 sound beings, all representing the same brain function across all individuals. This field design highlights simultaneous explorations between them, promoting a comparison focus on one brain task activity.

[3] https://vimeo.com/945536336.

3.2.2 Event Recognition

The main input is a *dragging movement*, interpreted by one *translator* as the participant's movement. Three other *translators* are responsible for the mouse interaction with the sound beings, detecting 1) a *click* that attaches the corresponding sound being to the participant, joining their movement; 2) a *release* that fixes it in the current place; and 3) a *double tap* that detaches the sound being, returning to its original movement. These interaction controls allow the participant to rearrange the sound beings as desired.

Data-related changes are read by two *translators* through inputs from the arrow keys: in the first design option, to change the data stream of chosen individuals (*up/down* changing the experimental group, *left/right* the control group), which allows the exploration of multiple pairs and combinations of individuals; and in the second design, to change the current brain region being sonified (*left/right*). These interaction commands focus on offering controlled attention to specific data streams.

3.2.3 Event Processing

The presence of the participants near the sound beings is regarded as an expression of interest, with the *signifiers* modeling this attention with a time counter. The attach/release gestures are, respectively, understood as a spatial composing objective, anchoring the sound beings to their current place or freeing them to continue their wandering. These intentional explorations can provide opportunities for comparing, overlaying, contrasting, and composing the sonic field with the sound beings, enabling diverse modes of listening (background listening, listening-in-readiness, and listening-in-search [19]).

3.2.4 Data Processing

Data listeners receive the incoming values of each timepoint at the defined tempo (14 values relative to the seven brain regions of two individuals, or 24 values relative to one brain region of all participants). These values are interpreted by *data signifiers*, namely a differentiator, which calculates the difference between successive values in the data stream. This analysis highlights changes in the ongoing cognitive function activity.

3.2.5 Sound Composition

Generators create initial leitmotivs for all the sound beings, with all following the same set of rules regarding the leitmotiv's tempo, key, mode, octave, and number of notes. The intention with this uniform initialization is to allow variations between brain functions and between individuals to sonically emerge during the interactive exploration.

The *melody composer* is attentive to human interaction, adding one note to the sound beings' response for each 5 seconds the participant is nearby. Each note is randomly chosen from the initially defined scale and octave and then added to the leitmotiv, increasing its size and the time needed for each leitmotiv loop. The *rhythm composer*, on the other hand, runs whenever a new data point is retrieved. Depending on whether the value is higher or lower than the previous one, the tempo of the respective sound being increases or decreases proportionately. This design assumes changes in the melody triggered by human interaction, and in the rhythm coming from the data stream.

3.2.6 Sound Rendering

Seven *performers* are responsible for seven instruments, whose perceived location in the soundscape is determined by the loudness and panning relative to the participant's cursor position and orientation. In the second scenario, there are 24 *performers* for the 24 sound beings, where they can translate the same or different instruments, with particular expressions.

Multiple design opportunities arise from applying the model as a design tool to create the interactive experience, with varied exploration and comparison opportunities depending on the chosen design. We next present an initial evaluation conducted, using the model as a mediation tool to discuss the design space with two data domain experts.

4 PLURALISTIC WALKTHROUGH

With one of the main design features regarding the multistable understanding of the dataset [21], this proof-of-concept was developed in collaboration with two data domain specialists (a biomedical engineer and a psychologist working in Biomedical Sciences, author of the study that gathered the dataset [27]). The authors conducted a Pluralistic Walkthrough methodology [31] with these two domain experts (and possible users), aiming at gaining initial insights on how they interpreted the developed prototype, while discussing design variations based on the model. This method is applied as an early stage usability evaluation approach, in which the users are guided through a demonstration or experimentation (usually simulated on a low-fidelity prototype) by a moderator, leading to subsequent discussion.

An initial exchange with data domain experts was conducted to understand the scope, aims, and specificities of the neuroscience study, which sought to investigate the differences between the ASD and TD groups, regarding the activated brain areas depending on the task at hand. Participants were instructed to explore a supermarket scenario and buy a list of grocery items, with sub-tasks that included a sequential order to pick up items or help an avatar-person. There was a predefined model, with the patterns of activation that were expected to occur, with which each run was compared to understand how much the collected reactions were close or far from the base model. Results showed differences between groups, in time and distance to complete the tasks and in the activated networks, with the ASD showing an hypoactivation "in the parahippocampal gyrus, involved in scene recognition" [27] and a simultaneous hyperactivation in the other areas, regarding executive, saliency, and social cognition. Details of the experiment, data gathering and processing can be found in [27].

4.1 Methodology

Retaking, as possible, a phenomenological *epoché* attitude that suspends pre-expectations from results [17], the design walkthrough was conducted following the steps:

1. a general overview of the prototype, explaining the sound beings and possible interactions;
2. illustration of the two alternative organizations of the sound beings (namely by group and by brain region) and how the design space is structured in each one;
3. demonstration of the distinct sonic responses, evolving with participant interaction and data influence.

4.2 Discussion and Insights

Both experts, focused on data analysis, portrayed the sonic field as a field of comparison between individuals, independent of their group. Highlighting the neurodiversity as a quality emerging from exploration, they strongly agreed with having similar rules for the initial leitmotivs. They also found useful the feature of attach/release for grouping the sound beings, suggesting to maintain the visual representation of the sound beings, to more consciously explore their arrangements and varied groupings.

One of the proposals for evaluating and further using the prototype was a grouping task for each cognitive function. In the first design alternative, the authors could seek how the participants grouped the brain areas responsible for the same function (e.g., the Ventromedial Prefrontal Cortex and the Middle Frontal Gyrus regarding decision making). Experts suggested two options: to have two individuals (one from each group) as it was, or just one at a time, grouping the brain regions for all 24 subjects in a row, in a randomized order. They found the second design scenario more useful, focusing on how the participants could differentiate all the individuals by group (ASD or TD), depending on the activation of selected brain areas. They suggested that two sequential tasks could be solicited to participants, to check if a grouping match was reached: the first representing one of the areas that showed an hyperactivation in the ASD group, and the second with one that showed an hypoactivation, to find if the groups were correspondent in both tasks. The final goal, in their words, would be to explore the potential to *"classify a clinical function through sound"*.

The discussion with the data domain experts, although only two, already provided key insights and design directions for subsequent versions of the prototype, resulting in design changes at each model stage and related agents:

1. **Interactive Sonic Field**: twenty-four sound beings move around the field, each for one brain function of one individual. We opted to provide a visual representation of the sound beings (alongside the participant's cursor), using it as a complement to the sonic field's exploration and grouping task, while not disclosing group identity to prevent user conditioning.
2. **Event Recognition**: all the main movements were found useful (*drag* to move, *click*, *release* and *double tap* to respectively select, fix and release a sound being), as well as the *arrow keys* programmed to change between data streams. Due to the high number of sound beings and complexity of the comparison task, additional keys were added: a) to mute/unmute one sound being, which enables individual focus; b) to unmute all the sound beings; and c) to release all the sound beings from their fixed positions, which restarts the grouping task.
3. **Event and Data Processing**: no design changes were applied in these stages.
4. **Sound Composition**: the authors maintained a *melody composer* attentive to human interaction and a rhythmic one following successive value differences in data. The data experts suggested, to emphasize these differences, that the *melody composer* also produced an octave change (departing from the one established in the beginning), increasing or lowering it according to the value variation.
5. **Sound Rendering**: the authors uniformized the chosen timbres, maintaining a single instrument to represent all individuals. This promoted sonic differences to be perceived due to data variations and user interaction, enhancing the sonic distinction between neurodivergent and neurotypical data without timbric influence.

The systemic model, besides being a design tool to conceive the interactive artefact, served as a mediator to debate the design space with data domain experts, promoting a dialogue that discussed and expanded design opportunities.

5 REFLECTIONS

The ability to address design changes in a structured manner demonstrates the potential of the model for guiding the design, implementation, and discussion under the systemic sonification approach. The authors now reflect on how the model translates the living system concept, generating dialogues that may go beyond the sonification research field.

5.1 Living Systems

Deep ecology, the paradigm shift Capra proposes [16], regards humans as a part of the environment, where every, single, interconnected part forms a web of life from which life is sustained. A living system emerges from the intertwined relationship of all its elements [32], whose combinations, rearrangements, and exchanges cause a natural evolution towards complex forms. A systemic sonification offers a dialogic soundscape that emerges between the participants and the sound beings. Through the iterative exchanges grounded on the mutable structure of the sound beings, patterns of perception for each participant are formed, constructing the living system's network that translate the meaning multistability of the sonification experience [21].

The sound beings are the core entities that sustain life within systemic sonifications, whose systemic structure stands from the interconnected roles of agents. The systemic division of the sound beings into design concepts

translates distinct forms of agency, where each agent works towards the assigned task. This agency also enables a cooperative behavior: through agent coordination, the system stages are processed to create the interactive sonic field. We can see this in how, for example, the *translators* read the dragging movement in both exercises, the *signifiers* then understand the presence of the participant as interest, which then leads the *melody composers* to add new notes to Ernie and the sound beings of the second experience. The proposed design model translates the living system in its structure, grounded on the relations between the agents and how they cooperate for developing the interactive field.

5.2 Generative Dialogues

With "opportunities for meaningful dialogue" [33], the systemic approach offers an open exploration and interpretation of data through 1) multiple design approaches and 2) multiple interaction paths for each participant.

5.2.1 Generative Design Space

Regarding the first potential, the design of the presented proofs-of-concept begin to demonstrate what we call a *generative design space*, where designers can explore multiple design variations in data mapping and interaction opportunities, and how they contribute to the aesthetics of sonification experience as a perception expander [21].

Generativity here comes from the concept of *generative potency* [34], proposed by the social psychologist Kenneth Gergen as a feature that translates the capacity of a theory to incite new alternatives. This generative potency can be seen in practice in the multiplicity of ways we could explore the agent concepts to redesign the personalities of Bert and Ernie and we could play with them, both in terms of sonic dialogues and by extending interactive gestures. The second exercise demonstrates how one could, at each stage, use both the data sources and human interaction to generate interaction gestures and the sound beings' chantings (as the sonic responses that evolve with the participant's interaction). During the development of the prototype, the authors envisioned alternative designs: what if the *composers* inverted their roles, with the *rhythmic composer* translating human interaction and the melody composer data variations? Or if another gesture translation was used (e.g., a rotation gesture), read by *signifiers* as an intention to induce an octave or a mode change of nearby sound beings? We could also have a *composer* that triggered a change within the *performers*, altering the initial timbre. We can also combine different cognitive functions to offer new opportunities for data exploration and interpretation.

5.2.2 Generative Artefacts

Ongoing discussions between the authors (and also pointed out by one of the reviewers) have envisioned how memory could be explored through complex, adaptive features regarding all the agents, carrying self-evolving intentions that guide the stream of actions. Dialogues could be supported by designing mutable sonifications that adapt with interaction, through the following:

1. adaptive *translators* that adjust to the participant's movements;
2. adaptive, memory-based *signifiers* that adjust to recurrent usage patterns;
3. adaptive *generators* and *composers* that evolve with each listener's abilities, or adjust to data patterns;
4. adaptive *performers* whose expressiveness evolves with external inputs.

This evolution capacity of our agents has not yet been explored in neither of the presented exercises. This includes the role of the *collector*, as the inherent concept of memory within this agent carries complexities that demanded deeper explorations. The design walkthrough was also manually conducted and adapted during the session. The adaptive potential of the systemic design opens a future branch of research, aiming to study the technical and algorithmic implementations necessary to explore these agent combinations and real-time adaptive features.

5.2.3 Mediation Potential

The model was applied as a mediator tool in a co-design collaboration with experts, wherein the key concepts map a generative design space that enables a dialogue with data domain specialists. The design space that grows with the systemic approach creates novel interaction possibilities to be explored for sonification, which may multiply themselves during iterative design stages in co-design approaches, which remain as a future potential to be explored.

The authors have not yet extended the evaluation of the model near design and/or sonification experts nor regular users. The authors argue the potential of the model grounded on the design and development of the two exercises, which stand as illustrations of how the model can guide sonification designs. The collaborative exchanges with the two data domain experts have also been conducted not only to discuss the design choices but also to demonstrate how the model becomes an organized dialogic space through which the design evolves. Next iterations will include experimental evaluations with non-expert users to evaluate the perception and interaction with systemic sonification to understand how the meaning-making paths unfold in multiple interaction paths and how the intended malleability of interaction supports this exploration.

5.2.4 Generative Interactions

At first glance, it may seem that context is predetermined by the dataset and the designer's choices; there is, indeed, a coded potential. However, the systemic approach is primarily dependent on the participant's interactive exploration of the sound beings (and emergent sonic dialogues), enabling the second dialogic potential of the systemic sonification.

There is a diversity of variations in how the sound beings can be arranged, creating varied compositions that offer different perspectives for interpreting the datasets. Human interaction is, ultimately, the driving force of the systemic approach, which welcomes the intentionality of each participant through a diverse potential of explorations

and sense-making paths. This multiplicity of interaction paths, leading to diverse data interpretations, is what we call *generative interactions*. The mutable artefact changes according to the actions of participants, who perceive those changes and assigns them meanings, ultimately contributing to their action-perception processes.

5.3 Alternative Implementations

The systemic model can be applied in alternative interfaces, where the *translators* could receive whole-body movements and gestures from motion sensing devices, varied touch inputs (as in [22]), or even wearable sensors that could induce changes in our *composers*. The auditory output, in its current stereo setup, is arguably not ideal. Other combinations, specially in larger or room-size interfaces, could explore surround combinations regarding spatialization, promoting more complex scenarios to perceive and interact with the sound beings.

5.4 Boundaries of Sonification

With the aim of generating interactive sonic fields, the systemic sonification paradigm can motivate a comparison with Interactive Sonification, in particular with Model-Based Sonification (MBS) [13]. They both share a common goal of implementing a data-to-sound mapping and generation, reacting to interaction stimuli that comes from user exploration. In MBS, there is a systemic approach to objective mapping, producing a sonic output based on data and user stimuli, which adheres to the goal of objective listening. Exploring the design space of systemic sonification opens the door to designing interactions that feed action–perception loops [18, 23, 21] based on data, stimuli and memory of exploration. These personalized and contextual paths feed subjective perceptions, which may lead to multistable appearances and interpretations.

A final thought reflects on how systemic sonification explores sound interaction phenomena: by sonifying interactive exchanges that occur within the experience itself, can we still consider systemic sonification to be a sonification? According to Hermann [35], we have a sonification when 1) it translates objective properties of data, 2) is reproducible and extensible to other datasets, and 3) uses a systematic approach for the composition process. Regarding systemic sonification, the sonic emanations from the sound beings translate subjective relationships that emerge through interactive exploration, instead of translating only objective properties of the data. As an adaptable system, its transformation grows from systematic to systemic, whose structure may initiate from a systematic mechanism of translation, but is permeable to external forces that influence the ongoing mechanisms, embracing a systemic thinking and design. We can consider that the initial structure of such a system is deterministically reproducible with varying datasets; however, its exploration is highly contextual, relying on the participants' intentionality and their interaction sequences, and how they perceptually explore the sonic space. In the end, the focus becomes the design of a sonification space from which experience emerges, born from the dialogues between the participants and the sound beings (and not only the quality of objective mappings).

If one assumes that the focus is on the experience that emerges through interaction, the systemic sonification paradigm opens possibilities within a larger design space for interacting with sound. Both of the systemic design exercises can be seen as examples on this spectrum, either as sonification exercises (the first of interaction itself, the second combined with a data source), but also seeking novel forms of interacting with sound. The authors argue that the systemic approach is generative in its application as well, moving past the field of sonification to be explored in a vast spectrum of sound and multimodal research.

6 CONCLUSION

The systemic sonification is a recent design approach to sonification, which proposes a sonification as a living system. This system is composed by a community of sound beings, whose mutable structure and behavior respond to iterative and interactive exchanges with their environment.

The sound being, as a sonic manifestation resulting from the systemic setting, can be designed through a set of cooperative roles. Inspired by MAS, a six-stage design model for systemic sonifications is presented, aiming at designing interactive sonic fields that emerge from the interplay between sound beings and human participants. This model is grounded on a set of eight design concepts that, as modular pieces with distinct responsibilities and shared goals, architect interactive system designs.

Two proof-of-concept exercises demonstrate the systemic model in practice, one as a play experience, and the other as an interactive field of neuroscience data. By applying the systemic model as a design tool to devise the interactive artefact and share its design space with field experts, we demonstrate how it can serve as a guidance tool to create generative design spaces for sonifications.

The systemic structure of the sound beings, built on the cooperation between the agent roles, allows for their mutability to become a design feature of the systemic sonification. The mutable sonic artefact evolves with the participant's actions, with the interactive dialogues between the sound beings and the participants building the action-perception and sense-making processes for interpreting the data space. Through a generative interaction space that is malleable to each participant, a novel perspective over aesthetics is embraced, grounded on the subjective and expandable perception of the sonic field.

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