Dark Sonification: an Entangled Post-Interaction Multimodal Data Display System

Miguel Angel Crozzoli
miguel@hi.is
Intelligent Instruments Lab, University of Iceland
Reykjavik, Iceland

Abstract

Humans today inhabit an ever-growing datafied world, where computational systems mediate between human and data collections, shaping perceptions and thus decision-making. Interaction is at the core of these mediations, affecting entangled human-data relationality with and within the systems affording them. In this context, interactive multimodal data display systems become increasingly important for making sense of the complexity of our datafied world. However, how can we design data display systems that engage with human-data entanglement? In this paper, I introduce my PhD project called Dark Sonification, an interactive multimodal display system for data perceptualization through affect. Inspired by entanglement and the post-interaction waves in Human Computer Interaction, the system is conceptualized as a Baradian apparatus where human-data entanglements are understood through intra-actions, co-constituting both the display outputs and interaction. This project offers a perspective into data display design systems shaped by new materialism, allowing for meaning-making through the entangled experience of data exploration.

CCS Concepts

• **Human-centered computing** → **Interactive systems and tools**; *Interaction design process and methods.*

Keywords

Dark Sonification, multimodal data display, embodied interaction, entanglement, post-interaction, affect, human–data intra-action, new materialism

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1 Introduction

Humans are increasingly experiencing the world through technological interactions, created by computational systems that mediate between human perception and data. As data grows in volume and complexity within our datafied world, more entangled human-data relations become part of this mediation. In turn, this entanglement amplifies the complexity of interactions stemming from these systems' affordances shaped by human–data intra-action [2]. As data continues to expand in both volume and complexity, its impact on human experience deepens. In my PhD, I make focus on big data and new ways for its exploratory analysis, especially questioning what emerging meanings are hidden within these datasets, and how they shape human lived experience.

To explore and understand this digital landscape, interactive data display systems become increasingly significant. Some methods for big data exploration, such as visual analytics [9], multi-dimensional data sonification [3] [16], and affective computing systems [19], aim to reduce cognitive load and improve pattern recognition, allowing users to effectively explore hidden meanings in data. Zhu's [20] study on big-data-driven visualization and communication compellingly analyzes these type of approaches, highlighting structured workflows, graphical simplification, and optimized audience psychology to improve cognitive efficiency and user control. However, these approaches mainly adopt a user-centered design that positions data as passive actor, neglecting the relational dynamics between humans and data within the design process and further interaction [10]. Consequently, traditional approaches fail to notice the entangled ecological relationships between human and data throughout display design process and exploration. In contrast, Dark Sonification's data display design and output, focus on the dynamic and entangled relation between human and data within the system's affordances [2] [5] [17]. Following a data-to-display structured workflow, Dark Sonification offers an open design system that emphasizes the affective and embodied dimensions of interactive data design and exploration for meaning-making. Accordingly, how can design in data display systems articulate human-data intra-action?

Inspired by entanglement [5] and the post-interaction [2] wave in Human-Computer Interaction (HCI), data display systems can integrate human–data intra-actions by focusing on computational background services rather than direct user manipulation [18]. Hespanhol [8] characterizes these computational background services, such as machine-learning clustering, as stretched temporal processes that constitute high-level relationalities, continuously transforming data independently of explicit human intent. Conversely, direct interactions via embodied interfaces represent immediate temporal processes, defined as low-level relationalities centered around situated, perceptual engagement [8]. In Dark Sonification, interaction design is framed through this relational perspective, articulating how embodied interactions (immediate) influence and are influenced by computational background services (stretched). Moreover, temporal stretched processes are accessible through a

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transparent design framework that renders visible data transformations. This transparency provides direct insights into how computational processes shape phenomena during both design and data exploration. Accordingly, interaction design operates within, rather than upon, data transformations, where human-data entangled intra-actions through algorithmic agencies co-constitute the aforementioned phenomena. Therefore, by articulating both stretched and immediate relationalities, human-data intra-actions become a central factor for embodied interaction, expanding awareness of ongoing background transformations. Nevertheless, what embodied forms of knowledge are we experiencing through these background mediations?

Dark Sonification views affect as integral to perception and entangled with technological mediations. By designing interactions that engage in affective dimensions, particularly the felt sense –a bodily awareness of complex, unarticulated knowledge [7] [15], the system allows for meaning-making through pre- or para-linguistic forms of embodied perception [13]. This makes interactive data exploration more accessible and closely attuned to the sensual and emotional dimensions of human experience [14].

There is a growing body of projects that engage with entanglement or post-interaction conceptual frameworks as previously outlined. For instance, Loh et al. [11] designed a sensor-driven infrastructure that configures the office space as an entangled human-plant ecosystem. Similarly, Crossley-Lewis et al. [4] demonstrate a VR molecular simulation system, where real-time algorithmic recomputation allows users to create atomistic simulations, in line with human-algorithm intra-action and designing interaction for background computational services. These projects are part of an increasing interest for rethinking human-data-systems relationality.

Building on these conceptualizations, I introduce Dark Sonification, a multimodal interactive data display system conceived as a Baradian apparatus that structures the design process around data transformations, drawing attention to entangled human–data intra-actions within system affordances. Moreover, it addresses data perceptualization through affect, enriching meaning-making practices through embodied interaction.

2 Specific Research Objectives

The main goal of my PhD, is to create an intelligent multimodal interactive display system that allows for exploration of large data sets for data perceptualization though affect. Dark Sonification aims to offer scientists an embodied and performative tool for engaging closely with their data, gives access to general users to perceive and take ownership of the worlds data, and provides an instrument for artists to use data as a creative material. The project also looks into data agency within exploratory analysis. It explores how the system can learn from human gestures to enhance data exploration, assign specific behaviors to data streams, and create data-to-human feedback interactions. The core question of this research is: How can exploratory, intelligent multimodal display systems enable embodied cognition through data perceptualization and affect in Human-Computer Interaction?

3 Dark Sonification

3.1 Theoretical Contextualization

Dark Sonification is an interactive multimodal data display system built upon entanglement and post-interaction waves in Human-Computer Interaction (HCI). The entanglement wave, articulated by Frauenberger [5], emphasizes that phenomena emerging from computational processes are co-constituted through dynamic intra-actions between human and non-human actors. Concurrently, the post-interaction wave, described by Comber et al. [2], shifts attention towards computational processes occurring 'without' or 'outwith' direct human input, thus advocating for designing interactions that engage with these background processes. Taken together, these frameworks underscore the complexity of data display systems by recognizing data as a non-human actor within entangled human–data intra-actions.

Consequently, interactive multimodal data display systems like Dark Sonification are conceptualised as being co-constituted through intra-actions. This establishes a relationality among humans, data collections, algorithms, and system processes which aligns with Karen Barad's definition of an apparatus [17]. For Barad, an apparatus is a specific material–discursive practice or configuration, inseparable from and productive of the phenomena it enacts [5][17][1]. Reed et al. [17] conceptualize such systems as data-enabled artifacts, emphasizing that these artifacts do not exist independently from the phenomena they engage with, instead, phenomena and apparatuses mutually constitute each other. In a data display system context, this implies that the displayed output is a dynamic phenomenon rather than a neutral representation of data [18]. This perspective raises questions about how humans experience data exploration through these systems, and how system affordances facilitate human-data entanglements that shape perception [14].

Building on this understanding, phenomena become central to human perception, enabling experiential processes to unfold and facilitating meaning-making [6][14]. Here, phenomena are dynamically configured by agential cuts, which are material-discursive practices that enact boundaries between an apparatus and its environment [18][1]. In Dark Sonification, these cuts are iteratively shaped by both design choices and subsequent display interactions, emerging through intra-actions. Reed et al. [17] further elaborate on this by emphasizing that indeterminacy is a feature of phenomena, and agential cuts serve to resolve this indeterminacy into distinct subjects, objects, and localized cause-effect patterns. This process, however, has been characterized as messy and ambiguous [17][18] due to the constant renegotiation between phenomena and apparatuses, reflecting a dynamic, non-static reality [5].

To address this messiness and ambiguity in favor of clarity in meaning-making, Dark Sonification articulates the design workflow in modules following a high-order structure, where data transformation processes are categorized based on signal and symbol conceptualization. Following Magnusson's [12] signal and symbol discussion based on Peirce's trichotomy of the sign (icon, index, and symbol), we conceptualize signal as structural transformations that encode spatial/temporal relations, and symbol as contextual transformations that allows for comparative insights across the dataset (example of signal vs signal-symbol transformations in

sound design available in footnote[1]). Thus, within Dark Sonification's modular workflow, designers iteratively design and configure agential cuts as signal-symbol representations, rendering visible how indeterminacy becomes perceptible phenomena. Nevertheless, how do these transformations affect human experience of the phenomena?

Accordingly, my proposed data display system conceptualizes affect in the felt sense [7][15] to focus on the human experiencing of phenomena. Dark Sonification uses interaction to attune the body to its evolving perceptual field, letting meaning emerge from the interplay of human intent and system affordances [14]. This affect-driven experience echoes Gendlin's notion that meaning emerges from the interaction between experiencing and symbols [7].

3.2 System Design

The system's architecture is modular, integrating four interconnected engines: Processing, Mapping, Navigation, and Display. Each engine takes a form of data and returns the data transformed, ready for the next engine to structure and integrate further transformations. The **Processing Engine** uses machine learning and deep learning techniques to encode raw data into latent structures based on algorithmic configurations. The **Mapping Engine** contains visual, haptic and sound transformation modules. Each one of these modules fits the return from the processing engine and transforms the data into perceptual parameters. The **Navigation Engine** allows users to explore the data interactively via embodied controllers such as the PS5 gaming controller. Lastly, the **Display Engine** creates an environment combining the final output from the Mapping engine with the capacities of the Navigation engine, creating a human-data interactive environment with auditory, visual, and haptic feedback.

Each engine operates as an independent module with its own dedicated pipeline. The output of each module can be a passed-through Dark Sonification workflow supporting a continuous and clear data transformations flow. Inside of the modules, the system allows to assign signal or symbol labels to transformations, creating an overview on how transformation processes are defined and interconnected across the system processes. This labeling workflow enables designers to mix and match transformation strategies and fine-tune only specific module parameters. The modules' pipeline are build based on a fit-transform logic. Every module first fits the incoming data by learning and parsing, and then transforms the data according to the module definitions before passing it to the next module, clearly showing how data is received and returned at each stage (see Figure 1).

Dark Sonification contributes to the interactive multimodal data display design landscape by proposing the integration of entanglement and post-interaction HCI waves into a unified framework within interactive data display design systems. The system further re-frames exploratory data analysis through entangled human–data intra-actions co-constituting phenomena which allows for meaning-making through embodied interaction.

[1]https://shorturl.at/SVoOQ

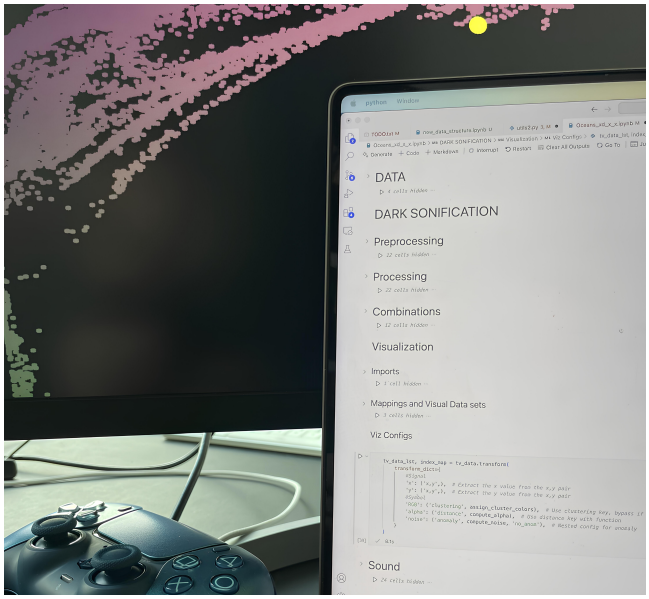

Figure 1: A Jupyter-based Dark Sonification implementation where the user adjusts scatterplot mappings under the "Mappings and Visual Data sets" panel (right), while operating a PS5 controller for spatial navigation.

3.3 A Brief Note on the Project's Name

The term dark is borrowed from astrophysics, referring to the perception of "invisible phenomena" through their influence on other things. In Dark Sonification, data turns dark after computational transformations and are perceived through the system's dynamic emergent phenomena. Sonification refers to the main medium through which the system anchors human experiencing, where meaning-making unfolds temporally through the contextualization of sounding data point alongside others. Nonetheless, the system has the capacity of displaying audio, visual, and haptic modalities.

4 Dark Sonification in Action: An Ongoing Ocean Data Case Study

I am using Dark Sonification to create an interactive audiovisual display for an oceanographer, to explore dynamic relations between Atlantic, Arctic, and Greenland water masses. The dataset comprises over 120,000 spatially located entries per day, capturing temperature, salinity, and biological indicators. The oceanographer typically creates static visualizations using scatter plots with color interpolations based on custom classification algorithms. One major challenge of their workflow is integrating new algorithmic processes, which limits experimentation with different computational transformations.

Through Dark Sonification's modular architecture, we expanded their usual data processes with PCA and K-means clustering imported from SciKit-Learn. We further introduced embodied interaction using a gaming controller to navigate individual data points, and data sonification. These implementations offered new ways

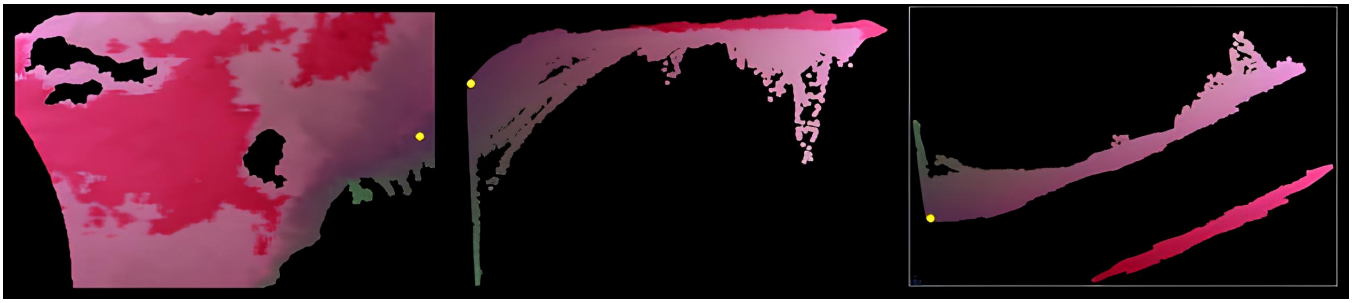

Figure 2: Dark Sonification exploration of ocean data through various computational transformations. From left to right: (1) spatial layout using latitude and longitude, (2) salinity vs. temperature scatterplot, and (3) PCA 2D embedding. All plots have the same custom classification coloring. The same data point is highlighted in yellow across all three views during navigation.

of examining the data's structure across perceptual and computational lenses. Early feedback from our oceanographer highlights the system's potential for generating new insights, particularly by enabling the tracing of how individual data points shift both structurally and contextually across transformations, and not only see the plots, but interact and listen to them. For example, comparing PCA layouts with the usual spatial mappings reveals different structural distributions that enhance clustering differentiation while still preserving key features like freezing point lines in the time series (see Figure 2).

5 Computing (after) Crisis: Reflection on the Conference Theme

In times of entangled polycrises in a world increasingly defined by datafication, Dark Sonification offers a new perspective on explorative data display and design systems by rethinking our engagement with data through embodied perception. Thinking Dark Sonification through "Computing after crisis," is an invitation to imagine data as a non-human actor, co-constituting humans' relationship to their environment, and to explore our understanding through a critical insight of our relation to data. In Dark Sonification, computing is a mediator of ongoing, relational, and dynamic phenomena, continuously shaped by human-data intra-actions, where data is entangled in the very fabric of human understanding, holding a powerful access to an embodied understanding of our current crises.

Dark Sonification, therefore, re-centers the body in data exploration for knowledge production, proposing a perspective where the human relation to data is not about solving, but thinking with and within. This perspective encourages practices of care and a political, embodied ethics in data exploration. Moreover, by focusing on affect through the felt sense, Dark Sonification dives into data democratization, rendering datasets accessible, inclusive, and attuned to ecological sensibilities through bodily awareness. Then, the chosen "after" for this reflection, signals a post-human take in Dark Sonification, where human-data intra-actions become ecological acts of relational becoming.

6 Previous Work, Next Steps, and Three Questions

I am building my research toward the dissertation through a planned series of papers. Sounding Numbers (ICAD 2025), examined the sonification object as interface and the role of aesthetics in line with the designer's intent. My upcoming ICAD 2026 paper introduces Signal-Symbol high-order structuring for data-to-display transformations workflow. Another upcoming paper for xCoAx 2026 addresses data perceptualization through affect, focusing on the felt sense for data exploration. I am now drafting a paper that introduces Dark Sonification, along with workshop results and user-test interviews.

From September, I will focus on papers about data agency in Dark Sonification, enacting data ecologies in extended autographic design, and a decolonial approach to data exploration in Dark Sonification. The library will be released on GitHub in September, followed by a GUI rollout in 2026. I am also in the course of finishing my collaborative case studies on Arctic-ocean and Icelandic-saga datasets.

Questions for the Doctoral Consortium:

(1) How can I improve the theoretical framing to avoid overload while preserving designing for entangled human–data intra-action?
(2) What UI strategies could lower the entry point for designers without Python expertise, while retaining the tool's open-ended approach?
(3) As a data-display design system targeting both scientists and artists plus general audience, how should I present and prepare the tool upon its release to address such widely different experts' fields and needs?

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