SIGNAL AND SYMBOL REPRESENTATIONS IN SONIFICATION: STRUCTURING DATA-TO-DISPLAY TRANSFORMATIONS

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ABSTRACT

Multimodal display systems offer great potential for perceiving and understanding the increasing complexity and volume of data in our contemporary world, enabling better accessibility and interaction. However, increasing data complexity generally results in further design challenges. To address these challenges, we present a structuring method based on signals representing data structures, and symbols representing data contextual qualities. While current research mainly focuses on mapping strategies and common idioms across modalities, our method integrates mappings as part of a broader range of data transformation processes. Through this approach, we structure data transformations to facilitate multiple modalities integration, thus evidencing designers' decisions throughout a cohesive data-to-display workflow. To evaluate our high-order structure, we developed a sonification of ocean data with complementary visualizations and conducted a formative workshop with two design practitioners (n=2) to gather feedback on its application. Initial results suggest that our structure helps organize the design process, supporting practitioners intent.

1. INTRODUCTION AND DEFINITION

As data increases in volume and complexity in our contemporary datafied world [1], the need to integrate multiple modalities into display systems for data exploration grows [2]. Arguments in favor of combining modalities include enhanced comprehension, improved accessibility, and enabling richer interaction with complex datasets [3]. The issue of complexity and data access is gaining attention, with increasing discussions on the democratization of data within the display community [4]. Furthermore, creating different streams of perceptualization could provide modes for perceiving data based on diverse capacities, thus improving data accessibility as reflected by Lan et al. [5]. Despite these advantages, integrating multiple modalities for data display presents challenges in ensuring perceptual consistency.

There is an increasing attention towards conceptual integration in audiovisual idioms. Enge et al. [3] discuss the need for structures that clarifies design intent and facilitate strategies to mapping data features between audio and visual display parameters. During the creation of multimodal displays, designers typically make strategic decisions to reinforce data perceptualization and comprehension, considering how data features overlap in representation across display parameters and articulating mapping strategies [3]. This process is crucial, as it directly influences usability and interpretability of the design [4]. However, mixing perceptual spaces from different modalities increases the complexity of affective perceptual relations [6][7], which can have a negative effect in achieving the projects intent. Therefore, clear and structured design strategies are central, but the question remains of how different modalities can be integrated.

Many multimodal display design approaches focus on mapping specific data attributes to perceptual features and trace this relation across design. Caiola et al. [2] provide an analysis of cross-modality mapping, clearly showing relations between different sensory parameters and their corresponding data features. However, cross-modality mapping does not always help to convey a structured and consistent meaning [6]. These discussions open possibilities for considering a high-order structured approach to multimodal display design, one that looks beyond mapping strategies to address transformation processes from data to display.

Drawing on Munzner [8], data transformation can be understood as both a structural process, where new insights are derived through computational operations, and a means of presenting the data "as is." In both cases, the data is transformed from its original form to display. However, not all transformations affect the data at the same level. Some transformations, such as dimensionality reduction, restructure the data itself, and thus create new relationships within data features. Others, such as clustering, enhance understanding by assigning identities or categories to data points. Additionally, operations like scaling data features to display parameters directly shapes how the data is perceived.

In this paper, we propose a high-order structure based on data transformations under the concepts of *signal* and *symbol*. Here, the notion of signal represents the structural dimension of the data, unfolding temporal or spatial aspects of the display. In our view, the best fit for signal transformations are continuous data types. Accordingly, this data can define position and depth of objects in visualization or frequency and amplitude variation of a sound wave, among other structural possibilities.

Conversely, the notion of symbol represents the contextual affect of the signal, adding perceptual meaning to the data point. Therefore, transformations under symbolic representation provide identity, categorization, or comparative insights across the dataset. In our perspective, the best fit for symbol transformations are discrete or categorical data types. Consequently, this data can define color identity of objects in visualization or modulate auditory qualities such as timbre, among other contextual or aesthetic possibilities.

The user plays a crucial role in organizing data types into a coherent structure for signal or symbol representation, as distinguishing between data types under this structuring can be ambiguous. Therefore, assigning data features, either continuous or discrete, to specific signal or symbol categories depends on the users intent and display goals rather than intrinsic data properties.

Based on our professional experience as sonification and sound designers, performers and composers, we created a data display prototype for ocean data, focusing on data transformations from data to display under the signal and symbol high-order structure. Our prototype was created using an interactive multimodal data display technology called Dark Sonification. We applied an audiovisual design approach centering sonification as the primary modality of display. We then ran a formative workshop with two design practitioners (n=2) to gather feedback on the usability of this structuring approach.

Drawing on that prototyping experience and the participants' reflections, we suggest that structuring transformations under signal and symbol representations can strengthen the perceptual relation of data features to display parameters, creating a transparent workflow based on transformation, thus increasing intent clarity for the user within and across design decisions and processes.

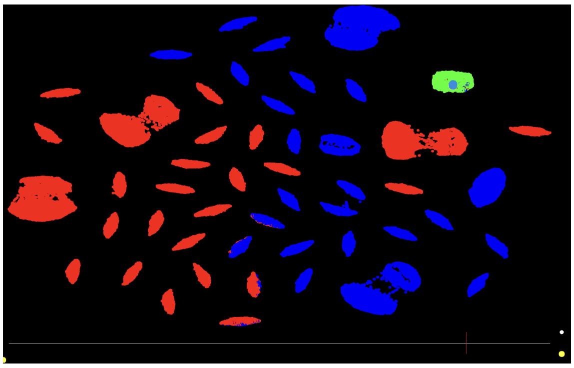
In the following sections, we contextualize our conceptual framework, describe the prototype and workshop methodology, and discuss the received feedback and reflections from our prototyping process and formative workshop.

2. CONTEXT

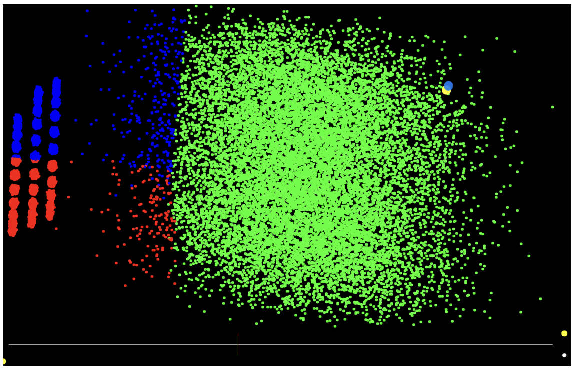
Taking inspiration from Magnusson [9], we can extend this discussion based on his conceptualization of digital musical instruments toward our multimodal data displays approach. Magnusson positions signal-symbol relationship by aligning it with Peirces trichotomy of the sign: icon, index, and symbol. He argues that icon and index signs reflect the quality or maintain a connection to their source, analogous to how data extraction in data collection processes tries to capture the intrinsic features of a source. In our framework, this quality is what we define as signal representation. In contrast, symbol signs are arbitrarily assigned processes which are based on conventions and determined by a population of users [9], parallel to how insights are derived in data analysis using machine learning algorithms. Consequently, this is what we refer to as symbol representations.

By presenting this structure, we advocate for a way of thinking design, positioning data transformations as central to articulate human perception in multimodal display. In our view, features structured into signal and symbol are arbitrary and based on conventions, meaning the perceptual dimension is not fixed but determined by context, aligning with Magnusson [9]. This suggests that the way signal and symbol is organized, influences how meaning is constructed within a given social and system context. Based on these premises, our high-order structure is adaptable and therefore dynamic, allowing for iterability and change based on the content of the structure.

For instance, think of a dataset whose dimensions have been reduced using Principal Component Analysis (PCA) or Uniform Manifold Approximation and Projection (UMAP), and clusters have been identified with a K-Means algorithm. By plotting PCA or UMAP transformations, data points along the axes will represent the inherent structure of the data (signal), and the use of color for the cluster identities learned with K-Means, adds a symbolic contextualization of the data points being plotted relative to one another. Here, transformations organized under signal representations are mapped directly to x,y position in a scatter plot visualization. In contrast, data coming from transformations under symbols is mapped to color identity (see Fig. 1).



(a) Scatter plot for UMAP transformation



(b) Scatter plot for PCA transformation

Figure 1: (a) UMAP and (b) PCA visualizations of signal representations, highlighting the distinct structures revealed by each dimensionality reduction method. The clustering labels obtained via K-Means are preserved and visualized using red, blue, and green colors.

Our proposed idea builds upon recent research in audiovisual display, which shows the benefits of implementing a structured mapping process for multimodal display design. Caiola, Lenzi, and Ricco [2] propose a mode to systematically organize mappings for audiovisual sonifications, improving coherence and effectiveness in data display design. In addition, Lenzi, Ciuccarelli, and Offenhuber [10] argue that a clear structure is required to translate data features into perceptual parameters to allow meaning-making for data-to-sound representations. Moreover, Walker and Kramer [11] offer an experimental assessment of mappings and metaphors in auditory displays, revealing that building mapping strategies through testing and a systematic approach can improve data perceptualization.

Within this systematic approach, Neuhoff [6] emphasizes the importance of carefully structured mappings, by considering a range of perceptual, cognitive, and contextual factors, concluding that sensory modalities influence each other. Similarly, Roddy and

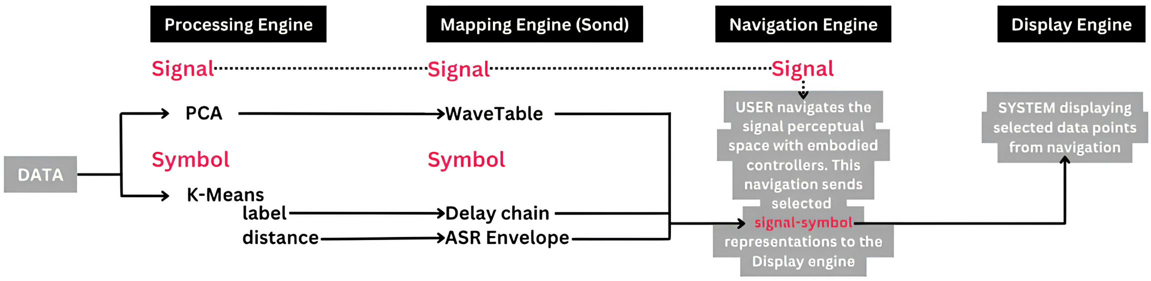


Figure 2: Example of data-to-display data transformation flow in Dark Sonification.

Bridges [12] address a mapping problem in sonic information design from an embodied perspective. Their research highlights that mapping data attributes to auditory cues must be designed in relation to the bodys natural perception and cognition. Thus, without a structured approach to transformation, the intended meaning can become obscured by arbitrary or inconsistent mappings, also supporting Neuhoff [6] argument that structuring enhances interpretation.

This context sets a picture where multiple efforts are concerted by looking at different modes for articulating data features with display parameters. Kim et al. [13] contribute to this discussion, by proposing strategies to integrate researchers and practitioners design knowledge, pulling different strategies and angles of expertise together. The call for thinking of a common idiom is clear in Enge et al. [3] and their analysis of the audiovisual design approaches and research network. Inspired on Munzner [8], Enge et al. [14] transpose the conceptualization of visual marks, channels, and substrates to think visualization design into the auditory realm, connecting idioms for audiovisual display design. Nevertheless, the solution, rather than being a single handled one, might be a pool of options for designers to be aware of and use based on their different cases. It is within this setting that we question, can high-order structures work as integrative frameworks for multiple idioms by prioritizing intent behind data transformations rather than mapping strategies?

Taking inspiration from Munzner [8] and parallel to Sedlmair et al. [15], we position data transformation processes as a key concept as one possible framework to address this common idiom issue. Munzner [8] proposes a three-part framework based on what (data abstraction and data types), why (task abstraction, such as exploration and presentation), and how (transformations like encoding, manipulation, faceting, and reduction). Additionally, Sedlmair et al. [15], distinguish three types of transformations: data abstraction, which involves transforming and deriving raw data to meet specific display needs; encoding, which entails scaling and mapping values onto appropriate display ranges to emphasize key attributes and enhance clarity; and interaction mechanisms, which enable dynamic filtering, interactive aggregation, and the creation of customized data representations. Our signal-symbol structure aligns with the how perspective in Munzner's [8] structured method for designing visualizations, and Sedlmair et al. [15] view on abstraction and encoding for data transformations.

The design process we describe in this paper is built around the signal-symbol workflow encoded in Dark Sonification, an interactive multimodal display system for embodied data perceptualization through affect. In this system every transformation is first labeled as either a signal (structural) or a symbol (contextual). Once defined, the labels remain consistent throughout Dark Sonifications workflow, providing users with a clear transformation oversight. Dark Sonification is an ideal tool for this approach because it organizes the data-to-display pipeline into **sequential modules:** each module receives data, applies a fit-transform operation, and passes the result forward. For instance, the data-processing module performs dimensionality reduction using a PCA algorithm, transforming high-dimensional data into a two-dimensional embedding and labeling this transformation as a signal representation. The resulting embedding is then passed forward to another module responsible for mapping it into audiovisual parameters. This second module receives the data labeled as signal and applies additional transformations through algorithms that are also defined as signal representations, resulting, for example, in specific sound timbres or spatial positioning. To test this method, we conducted a formative workshop with two design practitioners, focusing specifically on the signal-symbol structuring within Dark Sonification, described in Section 5.

3. DARK SONIFICATION AND SIGNAL-SYMBOL STRUCTURE

Dark Sonification is an interactive multimodal display system for embodied data exploration, created to reveal emergent meanings in complex data through affect. The architecture is designed to be 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 transformations within a clear and transparent data-flow. The Processing Engine uses machine learning and deep learning techniques to understand raw data from the user and returns a dataset with latent structures and analysis processes based on the designers needs and decisions. 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 by establishing processes or scalings between data features and display attributes. 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 (see Fig. 2).

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 flow of data transformations. Inside of the modules, the system allows the user to assign signal or symbol labels to transformations, creating an easy-to-follow overview on how transformation processes are defined, categorized, and interconnected across the system processes. This transparent and flexible labeling enables designers to mix and match transformation strategies and change specific module parameters to experiment with different possibilities to achieve the desired multimodal display representation.

An important feature of each modules pipeline is its fit-transform logic. In practice, 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. This provides to the user a transparent overview throughout the entire data-to-display workflow, as it clearly shows how data is received and returned at each stage. Moreover, the proposed structure also encourages an iterative design process, allowing designers to try different structural (signal) and contextual (symbol) transformations for each engine.

A first reflection from this project is that not every display technology is useful for a high-order structure. The chosen technology must afford to create a structure for data-to-display workflow that preserves both the structural (signal) and contextual (symbol) aspects throughout all transformation processes. Even though Dark Sonification has been specifically created for this purpose, the proposed structure is not limited to this technology. Mapping capabilities from projects like SC3NB [16] could be combined with transformation processes from libraries such as Scikit-Learn and visualization tools like Matplotlib to apply this framework. Nonetheless, to apply the signal-symbol structure by combining all these libraries would require a greater effort from the human side to trace and be aware of the data transformation flow.

Dark Sonification, by contrast, helps the user to perceive interrelations between different transformation stages and understand the entanglement between data and display through the system's affordances. In line with Sanches et al. [17], Dark Sonification is an open-ended back-end system that also functions as a front-end for design and interaction. This approach helps shift the focus of the previously mentioned common idiom issue, from mappings to a transformation-driven approach, as the user can attune with the system though data transformation flow, iterating over different possibilities to achieve the desired display.

4. PROTOTYPING WITH SIGNAL AND SYMBOL HIGH-ORDER STRUCTURE FOR OCEAN DATA

To test our signal-symbol structuring approach, we created a display prototype for ocean data from the Arctic region using Dark Sonification. This dataset was provided through an ongoing collaboration with an oceanographer studying changes in water masses. The oceanographer not only explained the properties of the data and corresponding ocean phenomena but also provided us with a custom classification algorithm for water mass. This allowed us to plan different transformation strategies following our proposed high-order structure, iterating over various processes, testing combinations of signal and symbol structures based on different algorithms. While the oceanographer supplied domain insight and tools that informed our prototype, a dedicated usability session and qualitative interview with him are planned for the next design iteration.

4.1. Data

For this prototype, we focused on a subset of the ocean data covering the first ten days of November 2023 from regions including the UK, Ireland, Iceland, and the eastern coast of Greenland. The dataset had 1.22 million entries extracted from satellite imagery, approximately 120,000 data points per day. Each row represented a specific geographic coordinate (latitude and longitude) and included 20 additional features detailing temperature, salinity, and other biological indicators related to phytoplankton production.

4.2. Transformations in Analysis

The data transformations implemented in our prototype were labeled into signal or symbol representations based on their continuous or discrete data types and their specific usage in oceanographic research. In the processing engine we implemented Principal Component Analysis (PCA) for dimensionality reduction, K-means clustering, a custom classification algorithm provided by our collaborating oceanographer, and the original geographic coordinates (longitude and latitude) used without alteration, aligning with Munzners [8] concept of data "as is."

Here, longitude and latitude coordinates, along with PCA dimensions, were used as structural dimensions of the display (signal representations). The use of raw geographic coordinates specifically provided a spatial visualization familiar to ocean researchers, enhancing comparability between structural transformations.

In contrast, the K-means and custom classification algorithms added contextual layers (symbol representations) by assigning categorical labels to data points. The custom algorithm classified points into Atlantic, Arctic, and Greenland water masses based on temperature and salinity thresholds. To maintain consistency, K-means clustering was also set to generate three clusters. The similarity between the classification and clustering algorithms was 89 %.

As a result, two transformations were labeled as signal representations and two as symbol representations. To evaluate how different combinations of these transformations affected the displays, we structured them into four distinct transformation pairs:

1. Signal: Latitude and Longitude; Symbol: K-means
2. Signal: Latitude and Longitude; Symbol: Custom Water Mass Classification
3. Signal: PCA; Symbol: K-means
4. Signal: PCA; Symbol: Custom Water Mass Classification

These pairings allowed us to systematically explore and assess the effectiveness of our method and perceptual outcomes of our display.

4.3. Transformations in Sound Design

For our data-to-sound representation, we decided to follow Li and Cox [18] conceptualization of DPS in audio and acoustic models. They propose a unified system for sound design as a combination of impulse and effects. Consequently, to apply our proposed high-order structure, we decided to label the categories of impulse as signal representation and effects as symbol representations. The data flow in our sound system followed a linear motion. Here, the first data-to-sound transformation was generated by the incoming data-signal from the Processing Engine into our impulse generator (signal representation). This created a continuous sound stream

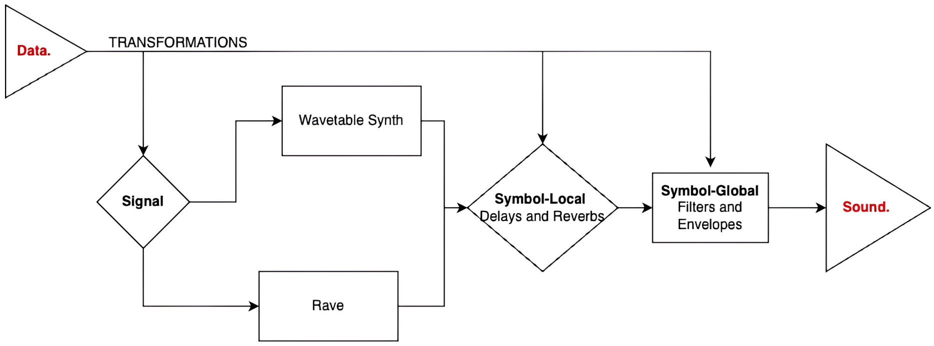


Figure 3: Data transformations flow chart for our prototype's sound design.

that flowed into a sequence of effects (symbol representations) altering the impulse through unique designed effect modules.

Moreover, in our sonification design, we used two strategies for mapping the signal, and a single strategy for mapping the symbol which is further structured into local and global variations. The first signal strategy translated the data, whether raw geographic coordinates or PCA dimensions, into sound by navigating a latent space generated by a RAVE model, a neural audio synthesis system capable of real-time encoding and decoding audio based on learned latent representations of a given dataset [19]. To find a latent representation in the RAVE model for each data point in our ocean dataset, we used a K-Nearest Neighbors (KNN) algorithm, creating a direct, one-to-one mapping from the datas structure to an auditory output. Then, as the user navigated the data, each data point was decoded into sound in real-time using an nn object in Max/MSP, similar to approaches in corpus-based concatenative synthesis in Schwarz et al. [20]. The second signal strategy employed a wave-table synthesis approach, wherein data-signal was converted into sound parameters by computing a set of partial frequencies and their corresponding amplitudes. The amplitude modulation was based on the proximity of each data point to its cluster centroid, as well as the distances to other centroids.

As for our single symbol strategy, we took the incoming signal, generated from RAVE or a wave-table, and processed it through sequences of delay, reverb, filters and envelopes. Within the symbol structure for sound design we created a two steps transformation process. The first step took the signal through sound scenes crafted after each classification category. These scenes were defined by sequences of delays and reverbs following the above mentioned symbol-local transformations. The combination of DSP modules were unique to each cluster id, creating three different sound scenarios that enhanced data points identity. The second step took the sound after these symbol-local output and further processed it through what we defined as symbol-global transformations. These were determined by filters and envelopes affecting sound parameters such as brightness, feedback and resonant frequency. Contrary to symbol-local, the symbol-global DSP modules were the same throughout all cluster id, creating a kind of DSP homogenization wall to process the incoming sound from symbol-local into an aesthetically uniform sound universe.

Further in detail, for our symbol-local sound design, we implemented the DSP parameter loudness to open and close dedicated chains of effects linked to datas cluster id. We also created different rhythmic patterns and spatial structures through sequences of reverbs following each one of the datas ids. The result of this design was three distinctive sound scenarios, one for each ocean type. In contrast, for our symbol-global sound design, we used pitch and harmony effects to modify filters and envelopes affecting the incoming symbol-local input. Here, we mapped classifications and clustering distances to the filters and envelopes parameters. This created areas of pitch resonance, dynamic frequency cuts, and further shaped the resulting sound through attack, sustain, and release (see Fig. 3).

After designing and testing our data-to-sound representation, we observed that a signal-only implementation generated unclear distinctions between data points. The wave-table synthesis provided slightly better differentiation, whereas the RAVE synthesis felt chaotic and lacked interpretability. However, combining both signal and symbol representations through our linear sound design, greatly improved the distinctions between data points based on their cluster identities. This reinforced the value of incorporating both symbol-local and symbol-global transformations in our data-to-sound design. Further collaborative refinement with our oceanographer colleague is necessary to adapt and optimize the sonification to their specific needs. A comparative audio demonstration of signal-only versus signal-symbol representations is available via the link in footnote. [1]

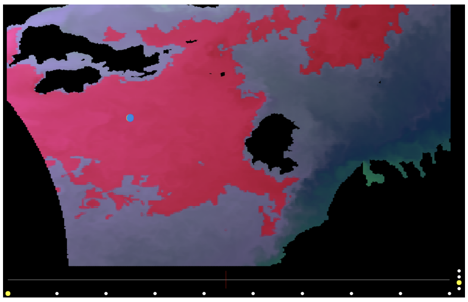
Overall, this sound design provided a flexible framework for iterating and testing different scenarios in the contextual transformation of data (symbol-local) while simultaneously ensuring their integration into a unified and coherent sound environment (symbol-global). This dual approach aimed to reinforce control over the perceptual dimension of data-to-sound transformation, helping to balance the specificity of local variations with the consistency required for a global sound identity.

4.4. Transformations in Visual Design

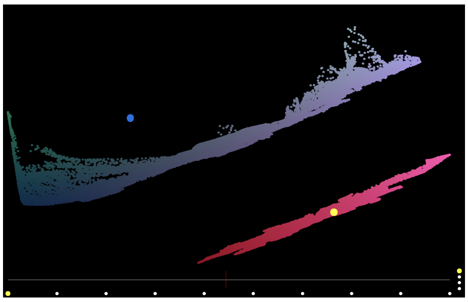
Although visual feedback was not the primary focus for this prototype, visual design in Dark Sonification plays an important role by allowing the user to set any degree of overlap across multimodal display parameters. For our prototype, the data-signal from the Processing Engine was mapped to an x, y scatterplot, where either the raw geographic coordinates or the PCA-reduced dimensions define the spatial positioning. Whereas for the symbolic structure, data points were color-coded based on their labels, assigning red to Atlantic, blue to Arctic, and green to Greenland water masses. Furthermore, to enhance perceptual differentiation, the visual engine modulates the transparency of each data point based on its

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

distance from their cluster centroid. Points closer to the centroid appear more opaque, emphasizing their centrality within a cluster, while those further away become increasingly transparent and may blend with adjacent clusters colors. This reinforces the contextual relationships among data points for the symbol structure.



(a) Visualization of ocean data: latitude and longitude features



(b) Visualization of ocean data after PCA transformation

Figure 4: a) Latitude-Longitude vs (b) PCA signal representations, both images colored after custom algorithm label classification for Atlantic, Arctic, and Greenland water masses.

5. WORKSHOP

We organized a formative workshop (n=2) to evaluate how our signal-symbol structuring approach is useful for multimodal display design, with a focus on how this structure helps to understand and clearly articulate projects' intent throughout the display process. The workshop was divided into two sessions. In the first session, participants received a theoretical introduction to the concepts of signal and symbol within the context of Dark Sonification. We explained how the system structures the data-to-display process through a series of modular transformations, and the importance of understanding and thinking of these transformations as signal or symbol representations. In this session, we used our ocean data prototype as a guiding example.

In the second session, we worked all together in drafting a new prototype using Dark Sonification. Participants had hands-on access to the systems multimodal capabilities, including interaction via a PS5 controller, audiovisual display outputs, and sound synthesis in Max/MSP. This session was designed to allow participants to experiment with signal-symbol method by structuring transformations throughout the data-to-display design process, and to observe how different combinations of transformations under signal and symbol structures influence design decisions.

The main participant in our workshop was a masters student, who was familiar with Dark Sonification but had not been aware of the underlying signal-symbol structure. His project involved creating an interactive sonification for sleep data, and our goal for him with this workshop was to provide insights into how this structured transformation flow can bring clarity to his design intent and improve iterative prototyping.

5.1. Feedback

After the workshop, our main participant, an artist and sonification designer, wrote a reflection as a form of feedback for the signal-symbol structuring approach. He expressed that designing based on transformations and organizing them into signals and symbols throughout different design stages brought clarity to his project. Furthermore, he noted a kind of conspicuous feeling by saying that the underlying distinction is already there, waiting to become apparent, in reference to signal and symbol.

Prior to the workshop, the participant had been attempting to sonify an ongoing project involving polysomnographic EEG data. By applying our proposed structure, he discovered that the incorporation of supportive classification algorithms allowed him to clearly differentiate between the primary data stream (signal) and the affective modifications (symbol). He described this structuring as a liberating shift in perspective, one that brought order to an otherwise overwhelming array of design options. He further confirmed that the framework facilitated easier iterative refinement, enabling him to maintain a stable signal while flexibly adjusting the symbolic impact. He further noted that this significantly enhanced his ability to achieve a clear design intent.

Interestingly, the participant also reflected on cinema as a metaphor to signal and symbol. In his view, signal being the visual part and the one encoding the intention of the design, is supported by sound that conveys emotion, atmosphere and underlying meaning, which he linked to the symbol representations. He also reflected on the non-binary nature of transformation processes, acknowledging that, depending on the projects intent, some transformations could fall into both categories.

Finally, he observed that "the value of the structuring is that it places, inevitably by definition, the intention as a pivot while the other parameters can move freely but not unbound," which deeply resonates with one of the cores of our project, to offer a structure that brings transparency to the data-to-display transformations flow, enhancing clarity of human intent throughout the design process.

6. LIMITATIONS AND FUTURE WORK

While our initial results suggest that structuring data transformations under the signal-symbol framework can improve understanding of data flow for multimodal display design, bringing clarity to the projects intent and facilitating iterative design, some limitations need to be mentioned. First, the sample size for the workshop was too small, involving only a single master's student and one additional design practitioner. Under these circumstances, a broader study is necessary to generalize our findings. Therefore, future studies should include a wider range of participants with varying levels of design expertise to better assess its usability, effectiveness, and engagement with the proposed structure.

Another limitation is that Dark Sonification was specifically designed to support the signal-symbol high-order structure through a modular, pipeline workflow. Integrating the signal-symbol structure with different tools might require a greater effort from the user to track and understand the transformation flow. This might lead to confusion and cognition overload affecting designers' process and experience. Specific studies to adapt this framework to other systems or collection of systems are required.

Additionally, our approach assumes a clear distinction from the human between structural transformations (signal) and contextual transformations (symbol). However, in practice, the boundary between signal and symbol can be ambiguous, and some transformation processes may not fit into one category or the other, but both. To address this issue, we might need to create case studies where transformations could serve as both and evaluate perceptual results of cross-transformation combinations.

Future work will focus on expanding the workshop with comprehensive qualitative interviews and exploring the integration of other display technologies to evaluate the robustness and adaptability of the signal-symbol high-order structure for multiple design scenarios, addressing also the issue of cross-transformation combinations. Moreover, we plan to run a comparative study in which design practitioners tackle the same data-display task, half using the signal-symbol workflow and half using their usual methods. We will assess the outcome through semi-structured phenomenological interviews to explore participants' experiences and follow up with a questionnaire capturing task-completion metrics such as perceived ease, cognitive workload, time on task, and number of design iterations. Finally, our next design iteration for the ocean data display will be carried out jointly with the oceanographer to collect feedback, and improve interpretability and domain relevance.

7. CONCLUSION

In this paper, we introduced and explored a high-order structure for multimodal display design, based on data-to-display transformations workflow. In our structure, transformations were organized into two categories: signal, representing data structural dimensions, and symbol, representing data contextual qualities. The main goal of this study was to test how structuring and being aware of data transformations influence the designers process and understanding of display output, stressing designers intent in connection with these transformation processes. We propose that this awareness facilitates iterative design.

To test our approach, we developed a multimodal data display prototype for ocean data focusing first on auditory display, and then extending our design to include visual modality. Additionally, we conducted a formative workshop with two participants (n=2) to gather feedback and understand the usability of our framework.

These initial experiments suggest that structuring data-to-display transformations into signal and symbol improves iterability and keeps focus on the project's intent by clearly demonstrating how data flows, evidencing how data features are transformed and connected with display parameters throughout modalities. Nevertheless, we acknowledge the preliminary nature of these results due to the limited number of participants in our workshop (n=2). Further studies with a larger and more diverse sample group are necessary to validate the framework across different technologies and contexts in order to generalize our findings.

8. ACKNOWLEDGMENT

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