Report from Dagstuhl Seminar 25072

What You Hear is What You See? Integrating Sonification and Visualization

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Abstract

This report summarizes the outcomes of a Dagstuhl Seminar that brought together international experts from the data visualization and data sonification communities. The seminar aimed to bridge these two fields by exploring their complementary potential in enhancing human-data interactions. Over five days, participants engaged in discussions, inspiration sessions, and presentations focused on nine key topics, including design theory, application examples, perception, interaction, and evaluation of integrated visualization and sonification. The seminar facilitated a collaborative environment in which both communities shared knowledge, identified common challenges, and began defining a novel field that combines visual and auditory data representation. The event marked a significant step towards establishing a common ground between these disciplines, with the goal of improving data analysis and presentation in an increasingly data-driven world.

Seminar February 9–14, 2025 – https://www.dagstuhl.de/25072
2012 ACM Subject Classification Human-centered computing → Visualization; Human-centered computing → Auditory feedback; Human-centered computing → Sound-based input / output; Applied computing → Sound and music computing
Digital Object Identifier 10.4230/DagRep.15.2.63

1 Executive Summary

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In our daily lives, we as humans perceive our surroundings in an inherently multimodal way. However, the vast majority of data analysis idioms are exclusively visual, not using the apparent potential of combined designs. While the visualization field studies visual data analysis solutions, the sonification field investigates comparable solutions that convey data over non-speech audio. There are several similarities between the methods and design

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theories of both approaches, such as the use of perceptual variables to encode data attributes, the use of marks and substrates to convey items, and the role of interaction in manipulating the data representations.

Over the last decades, both fields have established research communities, theoretical frameworks, and toolkit support. Although extensive research has been conducted on both auditory and visual representation of data, relatively little is known about their systematic and complementary combination for data exploration, analysis, and presentation. There are potential powerful synergies in combining both modalities to address the individual limitations of each other. Nevertheless, existing research on combinations has often focused only on one of the modalities.

This Dagstuhl Seminar aimed, first and foremost, at creating a space for discussion where the international communities of data visualization and data sonification came together to map and define a novel field for the improvement of human – data relationships. Over five days, 24 experts from both fields participated in group activities, inspirational sessions, keynote presentations, and informal gatherings. The seminar was the result of work conducted in the previous years by the organizers, including research projects, as well as a series of meetups and workshops and meetups of the AVAC – Audio Visual Analytics Community (`https://audio-visual-analytics.github.io`) at different venues:

- STAR and Panel @ EuroVis 2024 (Odense, Denmark): May 29-30, 2024
- Panel Discussion @ ICAD 2023 (Norrköping, Sweden): June 29, 2023
- Application Spotlight @ IEEE VIS (Oklahoma City, USA/hybrid): October 20, 2022
- 3rd Workshop on Audio-Visual Analytics @ Int. Conf. Advanced Visual Interfaces: June 7, 2022
- Workshop @ IEEE VIS (virtual): October 25, 2021
- Workshop @ Audio Mostly (virtual): September 3, 2021

Moreover, a State of the Art Report on data visualization and data sonification [1] was published as collaborative achievement of members of both communities. Based on these activities, the organizers identified a number of potential topics of discussion and shared them with the participants prior to the seminar. After an iterative, collective process of selection, we identified nine topics to be discussed in groups during the 5-day Dagstuhl Seminar:

- Design theory for joint visualization and sonification
- Design framework for joint visualization and sonification
- Application examples & success stories
- Tools and libraries
- Perception and cognition
- Redundancy and complementarity
- Interaction
- Accessibility
- Evaluation of joint visualization and sonification

During the seminar, after two inspirational keynote presentations that introduced the main achievements, techniques, tools, and challenges of both fields, participants were assigned to two topics of their choice, which they engaged in deeply in small discussion groups over the course of the week. Figure 1 shows the full schedule of the seminar.

The two *inspirational sessions* were designed as a light, engaging introduction for non-experts to visualization and sonification, and to provide a refreshing moment from the intense group discussions. In the evenings, participants gathered to showcase demos and current projects, exchange opinions on the respective fields, and overall enjoy each other's company. The excursion to Völklinger Hütte was an intriguing break that helped participants connect more deeply with the region that will provide long-lasting memories for the participants.

The work started during the seminar is far from being complete. However, we felt that great progress was made to bring the two perspectives closer together. The need to define a common idiom was a first challenge that became easier as the week progressed. Both communities made efforts to understand each other, which also involved self-reflection on one's field and open *eyes and ears* to the other's. Groups focused on mapping the borders of each field and began defining the key terms as a necessary preliminary step to build a new joint perspective. The sections of this document will report on each group's progress.

In a historical time when we as humans are dealing with the often overwhelming presence of data in our lives, and when researchers in the field carry the responsibility to facilitate sense-making of such data, this Dagstuhl Seminar has been widely recognised by participants as a milestone in establishing a common ground between the data visualization and data sonification community.

References

1 Kajetan Enge, Elias Elmquist, Valentina Caiola, Niklas Rönnberg, Alexander Rind, Michael Iber, Sara Lenzi, Fangfei Lan, Robert Höldrich, and Wolfgang Aigner. Open Your Ears and Take a Look: A State-of-the-Art Report on the Integration of Sonification and Visualization. *Computer Graphics Forum (EuroVis '24)*, 43(3):e15114, 2024.

Figure 1 Schedule of the seminar.

2 Table of Contents

3 Overview of Talks

On the first day of our seminar, we offered two talks and a self-introduction session, starting to build a bridge between the communities.

3.1 Sonification Background

Stephen Barrass (Sonification.com – Ainslie, AU)

This talk provided a background on sonification as a basis for sharing concepts and terminology with persons from the visualization community. At the beginning, some simple examples and a short historical timeline were presented. Next, canonical sonification techniques were introduced with examples. This was followed by an overview of more contemporary developments in techniques. Then, a final section introduced Sonic Information Design as an intentional approach using the *TaDa* Task-oriented Data Sensitive method for choosing a sonification technique.

3.2 Introduction to Information Visualization

Bongshin Lee (Yonsei University – Seoul, KR)

Information visualization is a powerful tool for understanding complex data by transforming it into visual representations that leverage human perception and cognition. In this talk, key concepts of information visualization were introduced for those new to the field, explaining why we visualize data and how it helps reveal patterns, trends, and insights. The role of interaction in enabling users to explore and manipulate data was discussed, making visualization a dynamic and engaging process. Additionally, the main purposes of information visualization, from exploratory data analysis to effective communication were covered. Finally, key challenges and opportunities in the field were highlighted.

3.3 Getting to know each other

Katharina Groß-Vogt (Universität für Musik & darstellende Kunst – Graz, AT)

First, fully embodied representation of the participants' backgrounds were enacted to sort along the alphabet (first names); along the time being in the research field; in 2D sorted on a world map; in 3D, stating your emotional feeling along valence, arousal, and dominance (lying on floor – standing). Then we conducted a speed dating on questions such as what is a good or bad example of sonification and visualization.

4 Inspiration Sessions

This Dagstuhl Seminar offered two *Inspiration Sessions*, one with a focus on audio and one focusing on visuals:

4.1 The Soundwalk

Kajetan Enge (Universität für Musik & darstellende Kunst – Graz, AT & St. Pölten University of Applied Sciences, AT)
Sara Lenzi (University of Deusto – Bilbao, ES & Ikerbasque Basque Foundation for Science – Bilbao, ES)

The "Soundwalk" is a practice born in the 1970s together with the emergence of soundscape studies [1, 2]. Soundscape is a term that refers to the totality of the sounds we hear in our acoustic environment, be it the sounds that we ourselves produce (breathing, walking) or sounds provoked by our interaction with the environment or by other agents in the close or distant world (e.g., cars, birds, airplanes...). Soundwalks are a tool that increases awareness of how we can explore and make sense of the world by actively listening to it. There are many ways to conduct a soundwalk. During this seminar, we selected and proposed to participants seven "Listening spots," both indoor and outdoor the Castle. Each Listening spot presented a suggestion for how to listen to the soundscape: "Imagine: Everything you hear is meant as a concert just for you," "Can you hear something that cannot be seen?", "How far can you hear?" ... Participants were encouraged to explore each listening spot on their own, in silence – some participants even found their own personal listening spots!

References

1 R. Murray Schafer. *The Soundscape. The Tuning of the World.* Knopfs, 1977.
2 Hildegard Westerkamp. Soundwalking. *Sound Heritage*, III(4), 1974.

4.2 Presentation and Activity on Alternative Designs

Jonathan C. Roberts (Bangor University, UK)

This session discussed design ideas to create many alternative designs. Starting with some background information on designs – looking briefly at an example by Jacques Bertin in his Semiology book – the session turned to getting participants in a group to consider alternative design ideas. The activity met the VisDice framework developed by Roberts and Owen [1], which used six inspirational images. In the activity, the image is chosen, and using lateral thinking, the people sketched a quick solution to visualize or sonify a dataset. The participants were split into four groups, each using the same test data. After sketching their own 2 cm x 2 cm quick sketch, they explained their idea to their peers. The next dice was rolled, giving a new dice image (inspirational image). The new idea must be different to the first. In this way the ideas change and are diverse from the initial idea. It helps to create new ideas. The process and ideology of generating alternatives were discussed, and the larger methodology of Five Design-Sheets [2] was also briefly presented.

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1 Aron Owen and Jonathan C. Roberts. Inspire and create: Unveiling the potential of visdice in visualization design. In Nan Cao, Barbora Kozlikova, Jiazhi Xia, and Wesley Willett, editors, *IEEE VIS 2023 Posters: Visualization & Visual Analytics*. IEEE Computer Society Press, 2023.

2 Jonathan C. Roberts, Chris Headleand, and Panagiotis D. Ritsos. Sketching designs using the Five Design-Sheet methodology. *IEEE Transactions on Visualization and Computer Graphics*, 22(1):419–428, 2015.

5 Working Groups

We structured our seminar in nine working groups.

5.1 Application Examples & Success Stories

Wolfgang Aigner (St. Pölten University of Applied Sciences, AT)
Stephen Barrass (Sonification.com – Ainslie, AU)
Johanna Schmidt (TU Wien, AT)
Kelly Snook (Kepler Concordia – Yamaguchi, JP)

The purpose of the *Application Examples & Success Stories* working group was to collect application examples and success stories for the combination of sonification and visualization.

5.1.1 Summary

The working group started the discussion with collecting examples of joint sonification and visualization, both in research and everyday situations. Especially when communicating the effectiveness of audio-visual feedback to people not familiar with sonification, the parking sensor in cars, metal detectors, and tools for localizing blockage in long pipes could be used as familiar examples. The working group continued the discussion by browsing the STAR report [1] and personal collections for audio-visual examples. From there, we identified key elements where sonification contributed to a data visualization. Afterward we looked into how visualization adds to sonification. A table was created that summarizes advantages for designers when using an integrated audio-visual approach. A list of application domains where audio-visual techniques are already used was created. The working group concluded the discussion by collecting examples of real-world situations where both audio and visual channels are required. Further developments could include the identification of real-world examples where both modalities are essential.

5.1.2 Application Areas

When looking at different audio-visual examples, we identified the following application areas where sonification and visualization are already used in combination:

- Astronomy
- Earth Science, Climate Change
- Physics
- Medicine and Health
- Molecular Science
- Biology, Zoology
- Social Sciences
- Economics
- Urban Studies
- Data Journalism

5.1.3 Results

We identified use cases and tasks where each modality (sonification and visualization) can profit from integration. Table 1 summarizes task and use cases where adding visual content to a sonification brings advantages to the analytics. Table 2 summarizes task and use cases where adding audio to a data visualization brings advantages to the analytics.

Table 1 The first column defines the task or use case that can be improved by adding visualization to a sonification. The second column describes the advantage for the potential users of the application.

Explore details	Audio can be used to set a context (e.g., bells give a comparison between different datasets/concepts). Visualization can then be used to explain the difference.
Exploration / Interaction	Visualization to steer the audio exploration of a dataset. Selecting details in visualization can help to focus on particular channels in the audio signal.
Orientation / Guidance	Point users to specific parts in the audio data which is interesting/important to listen to.

Table 2 The first column defines the task or use case that can be improved by adding audio to a visualization. The second column describes the advantage for the potential users of the application.

Sudden changes	We can hear sudden data changes better than we can see them. Rapid changes that are not shown very long (e.g., scrolling through a dataset) are hearable, but hardly visible and might be missed.
Small changes / Accentuation	Very small changes might not be visible (e.g., very little difference between bars), but these small changes would be hearable.
Repeating patterns	It is hard to see repeating patterns and compare them over time. This would work better when using audio.
Evaluation / Trust building	By not only watching a visualization, but also listening to a visualization, you can be sure that you did not miss anything and that you considered all small data changes. Audio may reveal uncertainty in a plot.
Different data scales	Listening to data from different data scales (e.g., tiny changes vs. large data scales) is possible, but visualizing data with different data scales is really hard.
More channels	With audio, it is possible to listen to more data channels than when watching the data (views get cluttered easily).
More foci	Possible to focus on a visualization (e.g., 3D representation) and hear a second parameter. Instead of switching between different views, audio can represent an additional channel (e.g., users select a data channel for audio and concentrate on another view).
More details	Different sound channels (e.g., for different data channels) can be heard and identified independently (if a dataset is constant or changing a lot). It is probably not possible to identify correlation.
Additional analysis channel	Adding audio can be compared to adding color to a visualization – it is then possible to represent, grasp and analyze more information at once.
Engagement	Sound/music can increase engagement, motivate people to watch a visualization, and help them understand the data. Users emerge while watching the visualization.
Increasing Trust	Sound helps to increase trust in automatic decisions of a machine (e.g., self-driving car, to indicate that it will turn or stop).
Feedback / Confirmation	When interacting with data, audio signals can be used for confirming the interaction (e.g., selection). Audio can be used to indicate the effect of an interaction (e.g., how many data points will be selected/removed by an interaction).
Transitions	Audio signals can prepare users for changes and transitions.

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1 Kajetan Enge, Elias Elmquist, Valentina Caiola, Niklas Rönnberg, Alexander Rind, Michael Iber, Sara Lenzi, Fangfei Lan, Robert Höldrich, and Wolfgang Aigner. Open Your Ears and Take a Look: A State-of-the-Art Report on the Integration of Sonification and Visualization. *Computer Graphics Forum (EuroVis '24)*, 43(3):e15114, 2024.

5.2 Perception & Cognition

Elias Elmquist (Linköping University, SE)
Katharina Groß-Vogt (Universität für Musik & darstellende Kunst – Graz, AT)
Michael Krone (Hochschule für Technik – Stuttgart, DE)
Sita Vriend (Universität Stuttgart, DE)

We argue for using multi-modal displays as they meet best the nature of human perception, following an ecological approach of how our senses were shaped and how they interplay to heuristically build up a representation of our surroundings.

The properties of audio-visual perception vs. cognition, i.e., the lower vs. higher level processes of Gestalt psychology, have to be clear to allow for creating truly multi-modal displays. Therefore, we intend to recommend a set of testable guidelines, still on a hypothetic level, that motivate mapping choices in audio-visual displays:

If you follow these guidelines for creating an audio-visual representation, the cognitive load might still increase compared to the load of the purely visual or purely auditory representation, but the least increase possible. It might even decrease! And – in any case – the user will also gain more insights.

Guideline hypotheses

- **Utilize principles of grouping in gestalt psychology and of cross-modal perception for both auditory and visual elements in the audio-visual data representation.** For instance, pitch can enhance brightness perception. Many more examples need to be collected here.
- **The A+V representation needs to be redundant in at least one data dimension, for instance either via a spatial/temporal synchronization or linked via interaction.** This argument is supported by the real-world synchronization of audio-visual events. Furthermore we draw on Munzner's [1] argument on visualizations: it makes no sense to have exactly the same visualization of the same data; but also not to show a different visualization of two different data sets. The benefit is showing either two visualizations of the same data or representing different data by the same visualization.
  - Any dynamic sonification should involve a dynamic visualization (e.g., showing the position in the timeline).
  - An overview visualization should be linked to an overview sonification!
  - A visualization can be combined with interactive sonification (details on demand!)
- **If there is a fully technically redundant A+V representation, question if there is any added value.**
  - Technical redundancy: all data variables map to visual variables and to auditory variables.
  - "Communicative redundancy" [2]: one modality allows for different insights (e.g., emotions in sound, engagement). We need more research here.
- **Sound has to be synchronous or a little bit delayed (and never earlier than visuals).** We find evidence for this claim in the Temporal Ventriloquism effect [3], though we need to add more details here from psychophysics research.

- **We *should* always use spatial sounds.** The evidence for this is the spatial ventriloquism effect, and the fact that all visualization is spatial. We should make use of spatial sound rendering in order to better align A+V displays.
- **Be clear in creating either consonance OR dissonance on the level of indexicality between A and V representation.** Indexicality [4] is the level between iconic and symbolic representation.
- **A good A-V mapping involves to separately (!) make sure the polarity of the audio representation and visual representation correctly represent the change in data value (semantics).**
  - Mapping should consider audio-visual correspondence AND the a-data and the v-data mapping separately.
  - Scaling of A-V mappings and mappable differences AV-data
  - Dimension of A and V should be considered

We discussed a number of further possible guidelines, but these need more research, either through literature review or our own experiments:

- List experimental findings on experiences of how we interpret AV representations uniformly. Furthermore, we can learn AV representations – find more evidence from multi-modal learning experiments.
- Identify saliency principles to guide attention in AV representations, and find which auditory properties relate to visual ones in their being salient.

References

1 Tamara Munzner. *Visualization Analysis and Design*. AK Peters, Boca Raton, FL, USA, 2014.
2 Kajetan Enge, Elias Elmquist, Valentina Caiola, Niklas Rönnberg, Alexander Rind, Michael Iber, Sara Lenzi, Fangfei Lan, Robert Höldrich, and Wolfgang Aigner. Open Your Ears and Take a Look: A State-of-the-Art Report on the Integration of Sonification and Visualization. *Computer Graphics Forum (EuroVis '24)*, 43(3):e15114, 2024.
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4 Dominic Oswald. Non-speech audio-semiotics: A review and revision of auditory icon and earcon theory. In *Proceedings of the 18th International Conference on Auditory Display (ICAD)*, Atlanta, GA, USA, June 2012. 18–21 June 2012.

5.3 Definition of a Research and Development Agenda for Integrated Audio-Visual Data Representation Tools and Libraries

Valentina Caiola (City University of Hong Kong, HK)
Thomas Hermann (Universität Bielefeld, DE)
Øystein Moseng (Highsoft AS – Vik I Sogn, NO)
Alexander Rind (St. Pölten University of Applied Sciences, AT)

We defined an audio-visual analytics idiom (AVAID), which is a systematic and reproducible audio-visual data representation. We followed a two-fold approach with a bottom-up phenomenological collection of current tools and libraries and a top-down scenario-based investigation with seven diverse personae. Outputs of the investigation:

a. Collection of categorization criteria for existing (visualization, sonification, and AV-integrated) tools, components and libraries
b. Identification of Interface Abstraction Levels – distributed on a continuum, where the two poles are (a) tools which are configured via a graphical user interface and (b) libraries/packages to be used for coding tools or components.
c. List of Requirements: List of needs and problems to be addressed by AVAIDs tools
d. Definition of minimal criteria for inclusion in AVAID tool set: **R**endering from **D**ata through a systematic representation **M**ethod (e.g., mapping, model) – DMR
e. Collection of Use Case Scenarios – along the interface abstraction levels continuum
f. Prototyping trade-offs

5.3.1 Defining the scope of tools and libraries

We defined **DMR** tools and libraries as complete systems that enable **R**endering from **D**ata through a systematic representation **M**ethod (e.g., mapping, model). We can differentiate between tools and libraries that facilitate this complete process, and components that support parts of this process. A full AVAID could for instance be setup as such:

- Data: a component to read/filter data (e.g., numpy for loading csv files),
- Mapping/Model: a component for mapping data (e.g., a python function to create a Csound score file),
- Rendering (Auditory Representation): CSound is a sound rendering component usable for sonifications that focuses exclusively on sound rendering (R).
- Rendering (Visual Representation): for instance the data could be plotted using scalable vector graphics (SVG) in the web browser.

5.3.2 Mapping the landscape of AVAID tools and libraries

We identified the following dimensions as useful for differentiating between AVAID tools and libraries:

- Platform (e.g., web, native, specialized)
- Environment (e.g., jupyter notebooks, IDEs)
- Self-contained DMR tools vs component tools vs. libraries
- Interface abstraction level (e.g., GUI, text, code)
- Popularity
- Licensing (open/closed)
- Learning curve vs. perceived value ("Return on time invested")
- Capabilities / versatility
- Data type support (e.g., map, graph, tabular)
- Data input/output, import/export
- Output capabilities
- Static vs dynamic output (interactivity)
- Visual rendering types (pixel graphics, vector graphics)
- Rendered audio types (sampled audio vs. score / higher level representation)
- Synchronization (e.g., between auditory and visual rendering)
- Collaborative editing or production features
- Extensibility

We believe the AVAID tooling space will need to cover a spectrum of different interface abstraction levels and levels of capabilities. This is analogous to the existing tooling space in visualization. Observing the current tools and libraries state of the art, we identified the need for audio-visual tools to develop AVAIDs, and came up with a narrow research question: RQ1: "What are the needs/problems that should be solved by AVAID tools across different interface abstraction levels?"

- functionality (services) matter more than rendering systems
- suitable rendering abstractions (to avoid engine specific lock-in)
- shareability/extensibility to promote community (presets, templates, extensions)
- enable (best) integration of the visualization and sonification modalities (synchronization, Multiple Coordinated Views (MCV) between modalities,...)
- Input/Output – Import/Export – Formats
- Users lacking knowledge of visualization and sonification – good output anyway – capture intent and context
- real-time rendering for enhanced interactivity
- continuum of flexibility versatility in data handling, method, and rendering
- data types (map, graph, tabular) and data size (performance)
- production speed (prototyping)
- collaborative production

5.3.3 Prototyping

We discussed how prototyping relates to AVAIDs and libraries and identified three dimensions that form a triangle of trade-offs:

- precision (or fidelity) (e.g., mock or subsampled data, imprecise representation method, or sketchy rendering)
- aesthetics
- speed (time needed to create prototype & products)

We acknowledge the speed quality trade-off in prototyping, speed referring to inverse time needed to create the prototype/system. Along the quality direction we usually face another trade-off, the one between precision and aesthetics, where the former refers to how accurately information is conveyed to the users and the latter refers to how pleasant and aesthetically the media is judged. Altogether, a ternary "prototyping space" emerges in which different AVAIDs can be positioned. AVAIDs may serve as an enabler of this process through their capabilities.

5.4 Towards a Design Framework

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Dietmar Offenhuber (Northeastern University – Boston, US)
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Creating audio-visual artifacts requires design. And design is hard, especially in an interdisciplinary setting. Nevertheless, Design as a discipline can provide the principles, processes, and tools that our field needs to produce impactful outcomes. Our main message is to be intentional, systematic, and interdisciplinary. This field will need to define its design patterns, best practices, and implementation strategies that achieve the design goals.

The design process as we see it starts with clearly specified Design Goals. These include hypotheses, purposes, intended insights, communicative intention, and potential outcomes. Understanding the ecosystem in which the AVA exists is crucial. The ecosystem is shaped by constraints, previous designs, and also future possibilities. The AVA Design Space is vast, requiring many decisions along multiple dimensions. Design Patterns can provide a process to navigate through the design space. Design Patterns can reflect the values, approaches, and best practices of our community. Finally, implementation can leverage all that is known about perception, cognition, aesthetics, communication, emotion, technology, etc., reflecting the depth of interdisciplinarity in the field.

5.5 Interaction

Mohammad Ghoniem (Luxembourg Institute of Science and Technology, LU)
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Jonathan C. Roberts (Bangor University, UK)
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Jonathan Zong (MIT – Cambridge, US)

When designing an interactive audio-visual system, we begin with data as the foundation. Our goal is to present information in a way that facilitates people to understand, learn, or engage in an enjoyable experience. The data itself shapes the auditory and visual experience, serving as the foundation of interaction.

Interaction enables individuals or groups to engage with the system, adapt their experience, and control the data exploration, and raises key questions: How is this system setup? What principles are there when setting up the system? How can we control the system and what actions do we enact upon the system? What devices are there to control the system? How do we display the output, and where is it displayed?

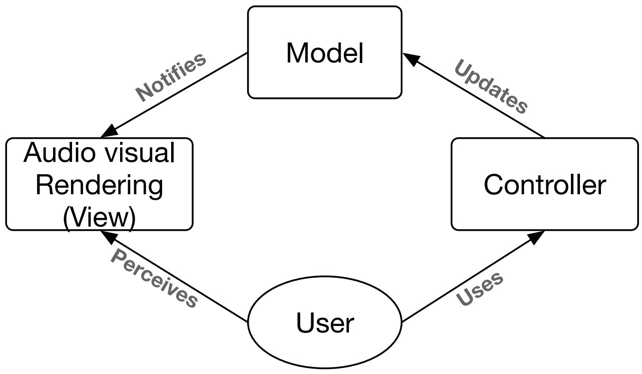

Figure 2 Model view controller for audio-visual renderings.

The model-view-controller (MVC) pattern, widely used in human-computer interaction [1, 2], offers a valuable framework for structuring these experiences (see Figure 2). In this context, we suggest using the term "rendering" instead of "view" because "view" carries a strong visual association. In contrast, both sound and visuals can be rendered, making "rendering" a more inclusive term for this discussion.

The *user* wants to understand the information, hear the data, and experience the visual feedback. There is an intent, an aim for their task. The data underpins the system. It can come from a sensor of the world (the distance from the car bumper to the tree) or from a questionnaire or survey (how happy are people in the world). Before it is rendered in visual or auditory form, it may need to go through cleaning, preparation and transformation steps to be ready for the audio/visual mapping. The result of this process is a *data model*. It is this data model that will be turned into sound and visualised. The user then interacts via a *controller* to express their intents, or goals, by controlling aspects or parts of the model that are rendered. The controller can be a device, an object of various shapes and materials, or more traditionally a slider on a user interface, button on a keyboard, or even their body in the world. The data-model now needs to be rendered – viewed and heard in some form. The *"rendering"* is a visual or auditory presentation of the data model, based on an output device, for example, speakers or screens in the room, or speakers or screens embedded in the objects that are interacted with, on headphones or in an immersed head-mounted display, mixed along with the visuals on a screen, handheld devices such as smartphone, tablet or small display such as a watch.

These ideas can be expanded and discussed further. Each of the individual parts, the model, rendering, controller and role of the user can be explored further. One important focus is that many instances of each part of the architecture are relevant. They are necessarily coordinated to provide a full and rich user experience. Multiple users can be in the system, interacting together, and controlling the audio-visual experience. Many renderings support multiple views or alternative presentations of the data. Various types of controllers enable different commands – some offering more intuitive interfaces, others designed for precise control, and some focused on enhancing user enjoyment. In addition, different controls, mappings, and experiences cater to specific needs, ensuring accessibility. For example, auditory feedback allows visually impaired users to engage with the system. People can also learn better when they can explore multiple and alternative ways of experiencing or interacting with the data.

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5.6 Accessibility

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The accessibility working group explored the role of multimodal audio-visual interfaces in improving accessibility, focusing on sonification and visualization. Discussions centered on the relationship between accessibility, inclusion, and usability, emphasizing the need for supporting diverse literacy levels and cognitive abilities. A key theme was redundancy across multiple modalities – how different representations can enable insights even if full redundancy across modalities is unattainable. We examined the balance between alternative and redundant representations, considering how auditory and visual modalities can enhance understanding without assuming that increased information bandwidth improves accessibility. The group also discussed strategies for achieving meaningful redundancy, including comparisons between perceptual mappings. We considered how interactive techniques can bridge gaps and link modalities – such as visually inspecting data while controlling sonification in time. The working group continues to discuss future research directions, highlighting the need for practical examples, interactive approaches, and frameworks that support accessible multimodal data representation.

5.7 Redundancy and Complementarity

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We developed the beginning of a redundancy-complementarity model for AV representations. Through discussions, which started with individual examples and understandings of redundancy/complementarity, we realised that redundancy/complementarity can be defined in the data, representation, and task domains. A **fully redundant** representation involves both representations (A and V) visualising/sonifying the same dataset and the user being able to do the same task with the audio-only, or visual-only or audio-visual representations. A **semi-redundant** representation might utilize two (or more) overlapping datasets, some visualised and others sonified. In this case, the sonification affords a task and the visualisation might afford a different task. A **fully complementary** representation involves separately sonifying and visualising two (or more) different datasets. These representations afford different tasks, but the fact that they are happening at the same time might make emerge an unexpected meaning that could be then used in some way, for example to create an art work. Furthermore, the group summarised possible benefits of these representations. Note that the following list of benefits is not exhaustive. A fully redundant representation might afford inclusiveness, the possibility of switching modality, safety and trust. The semi-redundant representation can afford engagement, reduction of cognitive load, representation of multiple dimensions (e.g., uncluttering), multi-tasking, richer understandings and trust. The fully complementary representation might afford the serendipitous emergence of a new/unexpected meaning, which could be beneficial in some contexts (for example an artistic context).

5.8 Towards a Design Theory

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The working group based its discussion on the Design Framework suggested by the earlier discussion group. We think of principles of Audio-Visual Idioms as encapsulating the Design Framework into a Design Theory. Four concerns that were identified are:

1. **Intention** – Intentionality: We suggest that in the context of audio-visual design, Intention refers to the deliberate integration of sonification and visualization by the designer in order to support sensemaking, presentation, and storytelling about the data.
2. **Integration** – different levels of integration (low → high):
   a. Hardware integration of output/presentation devices (e.g., speakers, headphones, screens).
   b. Technical integration: implementation of (combining) two modalities.
   c. Audio-visual integration consists in the coordination of visual and auditory renderings as they depend on the same underlying data (MVC Model View Controller Architecture [1, 2]).
   d. Sensory integration: integration of two (or more) perceptual stimuli. This is what comes from the real world, e.g., we hear and see a dog at the same time. This has to do with what our perception is exposed to. Sensorial perception is a requisite.

e. Cognitive/mental integration: it happens when a person understands the stimuli as coming from the same source. This association might be only imagined, a concept in our mind (vs sensory integration).
3. **Sensemaking**: We expect our audience to take an analytical perspective of our artifact (i.e., audio-visual artifact) in order to make sense of the phenomenon of interest.
4. **Artifact**: In our context, an artifact implies an audio-visual representation of a dataset. An audio-visual idiom (grammar) without data values is not an artifact.

Work on Design Theory will consist in identifying principles (such as unified constructs or a unified multiple coordinated AV-renderings framework) ensuring a deeper integration of the two modalities.

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5.9 Evaluation

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The purpose of this working group was to discuss evaluation of audio-visual (AV) idioms. First, we discussed the necessity for evaluation of AV idioms. Then, we identified evaluation methods from visualization, sonification, and human-computer interaction (HCI) and how they can be arranged into a decision map as guidance for researchers and practitioners. We discussed the special considerations for evaluating audio-visual idioms: auditory impairments, sound literacy (e.g., musician/non-musician), technical test conditions (e.g., headphones/speakers, room setup). Furthermore, the way how audio-visual idioms are not fully redundant makes it necessary to evaluate such idioms in an integrated way rather than visual separately from sound.

5.9.1 Why Evaluate AV Idioms?

We first discussed whether evaluation of AV idioms is always necessary. Some projects that involve AV idioms may not need to be evaluated. For example, the exploration of the design space and novel techniques may inherently be valuable and not need to be evaluated. The fields of sonification and visualization exhibit different trends in evaluating their research. While only few sonification papers include an evaluation [4], different forms of evaluations are widespread in visualization, which is (partly) due to publication venues often requiring an evaluation in order to publish. Of research on audio-visual data representations about two third include an evaluation [6]. Evaluation has the potential to reveal how an AV idiom is useful. Hence, we urge researchers to consider evaluation as part of their process, not merely as a formality.

5.9.2 Evaluation Frameworks and Methods

There is currently no framework or method for the evaluation of AV idioms specifically. Instead, we identified evaluation methods from visualization, sonification, and HCI. These methods can be used and adapted to suit the evaluation of AV idioms.

First, we like to point out evaluation methods from HCI. Evaluation methods from HCI are typically user-centered, meaning that the user is central to the design process. HCI distinguishes between formative and summative evaluation methods. Formative evaluation methods on the one hand are considered from the beginning and takes an iterative approach to the design of an artifact [27]. Visualization research has adopted formative HCI methods in visualization design studies [19, 25]. Summative evaluation methods on the other hand, are conducted at the end of a development cycle and tests how well a design performs. The design is often compared against benchmarks. Research in sonification and visualization often evaluates performance measures such as reaction time and error rate [15], but learnability [2], working memory load [22] and psychophysics [8, 23] has also been investigated.

From HCI and related fields, we identified the following evaluation techniques that would be useful for researcher to explore for the evaluation of AV idioms: (1) Empirical evaluation, (2) heuristic evaluation, (3) third-wave HCI methodologies, and (4) alternative methodologies.

1. **Empirical evaluation techniques** rely on experimental procedures to answer research questions. Experimental procedures can collect and analyze qualitative data such as in grounded theory [16], or quantitative data as long as the experiment is replicable. Validation of a data representation by comparing it to a second representation typically are empirical as well. Empirical evaluation techniques are widely used and accepted in visualization [17] and have been applied to sonification as well. Measures used in empirical evaluation vary widely and depend on the aspect a researcher would like to investigate. Some examples include standardized questionnaires such as the NASA-TLX on perceived workload [14], visualization specific questionnaires [10], questionnaires assessing usability of AV idioms [24], the visualization literacy questionnaire [18], among others. Visualization research has a rich tradition of mainly empirical evaluation techniques that could be adapted to evaluate AV idioms. For an introduction we could like to point the reader to *An Introduction and Guide to Evaluation of Visualization Techniques Through User Studies* [11] and *Patterns for visualization evaluation* [5].
2. **Heuristic evaluation** can identify usability issues in an artifact throughout the design cycles [20]. A heuristics evaluation involves a group of experts that examine and judge an artifact, often according to a list of principles. In HCI, many heuristic principles exist [21]. However, specific visualization heuristics have been developed [9]. We think that findings from psychoaccoustics and visual perception research could inform the design of AV idioms and could act as heuristics. There is an opportunity for future research to identify and formulate heuristics for AV idioms specifically.
3. **Third-wave HCI methodologies** go beyond the user-technology relationship and recognizes that interaction is a form of meaning creation. Methodologies thus focus on experiences and meaning-making in a broader context, beyond the artifact and its user [3, 13]. One such methodology is phenomenology: "a philosophical movement that seeks to analyze the relations between human beings and their world rather than as a method for describing reality" [26].
4. Lastly, we would like to point out **alternative evaluation methods**. We think such methods could be valuable to evaluate AV idioms too. For example: critical self-reflection, which is used in humanities [1, 7].

5.9.3 Special Considerations of the Evaluation of AV Idioms

Considering evaluation methods from adjacent fields is a good start. Such methods can be adapted to evaluate AV idioms. However, evaluations should be tailored to specific research goals. Hence, we identified special consideration for the evaluations of AV idioms. We came up with the following decision checklist to guide the evaluation of AV idioms:

1. **State the intent** of the AV idiom and possible hypotheses and assumptions: A design is usually created with intent. This intent should be testable. Additionally, the researcher should state their assumptions and expectations. These can be formulated as testable hypotheses.
2. **Define specificities:** Define who the intended user of the AV idioms is, what task(s) they will perform with it and in what context they will use it.
3. **Summative vs. Formative:** A researcher should decide how they intend to evaluate their AV idiom before they start design. Do they intend to involve the user throughout development? Then formative evaluation methods will apply. Or will the researcher compare the AV idiom once it is created? Then summative methods are better suited.
4. **Define "good":** Researchers might want to evaluate if their AV idiom is better than an alternative representation. In such a case it is important to define what it means for the AV idiom to be good. What good means depends on the intent and specificities of the designed AV idiom. For example, should the designed AV idiom lead to fewer errors or should the designed AV idiom be more memorable.
5. **Choose methodology and method:** The researcher should choose a suitable method based on the previous points. In both visualization and sonification, empirical methodology is often chosen. Empirical methods are especially suitable for summative approaches. This methodology include both quantitative and qualitative methods that can be used to validate a design. However, we also want to point to alternative methodologies from other fields. For example critical self-reflection which is commonly used in humanities, phenomenology which is widely accepted in design, and third-wave HCI methodologies.
6. **Choose measures:** What to measure should be chosen based previous points, especially on the methods chosen and what "good" means to the researcher. For example, a researcher wants to know if their AV idiom conveys the same information to sighted, deaf and blind users. In such a case, the researcher might chose a qualitative method to measure the users' comprehension of the AV idiom.

We recommend that researchers plan how to evaluate their AV idiom before they begin development. An AV idiom is often designed with a specific intent. This intent needs to be stated, as well assumptions and hypotheses. How to evaluate is guided by these intentions, assumptions and/or hypotheses. For example, an AV idiom is designed with the intent to help children learn about space. The evaluation should then test the learnability of the AV idiom with children.

Furthermore, design often requires specificity. AV idiom are often developed with a specific user in mind who will use the design in a specific context to perform determined tasks. These specificities need to not only be considered when designing the AV idiom but also when planning the evaluation. In the case of a summative evaluation, especially when looking to validate an AV idiom, a baseline must be chosen when evaluating an AV idiom. We concluded that AV idioms should be tested as an integrated system when exploring the design space of AV idioms. Hence, as a general rule of thumb, AV idioms should only be compared to alternative AV idioms. This is because Gibsodian perception [12], considers human perception as an active integrated system, rather than as passive and separate channels of sensation. This theory of ecological perception has enormous implications for the evaluation of multisensory interfaces! The whole is more than the sum of the parts. Evaluating channels separately will not provide a true description of the whole system. Furthermore the senses provide different kinds of information and a simply redundant interface is the least likely to provide perceptual benefits and advantages. Hence, it is not useful to compare visualization to AV idioms. However, we identified exceptions. For example, a researcher might compare an AV idiom to a visualization if they want to explore if the combination with sonification adds something useful to the visualization. Or if an AV idiom intends to be accessible for blind, sighted, and deaf individuals.

There are, of course, further factors that will influence the results of an evaluation. On the one hand, the background and personal factors of the user will play a role (e.g., musical training or auditory impairments). On the other hand, the technical setup will play a role (e.g., room/lab settings and the output device). Therefore, such factors need to be documented correctly and thoroughly considered when drawing conclusions based on the evaluation results.

However, we see the need for evaluation methods specifically developed for AV idioms. Further research should identify, adapt and extend evaluation methods from HCI, visualization and sonification useful for the evaluation of AV idioms. For example, how do we adapt evaluation methods to evaluate fully redundant AV idioms, fully complementary AV idioms, or mixed redundant AV idioms?

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6 Open Mic Sessions

In our seminar, we held Open Mic Sessions on Monday, Tuesday, and Thursday evenings in the castle's wine cellar. Mainly, the following topics and projects were presented and discussed:

- Jonathan Zong presented his work on *Umwelt* [2].
- Kajetan Enge presented *theoretical constructs* bridging the theory-gap between the sonification and visualization fields [1].
- Kelly Snook presented her MiMu Gloves[1], a pair of gloves for versatile music composing and performing trough gestural movements.

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[1] `https://mimugloves.com/`

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