Towards a Unifying and Accessible Data Perceptualisation Design Theory

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Abstract

To inform the design of visualisations, sonifications, data physicalisations and other multisensory interfaces, designers and researchers draw on insights, studies, resources and guidelines from a broad range of research disciplines. We have investigated opportunities and challenges of establishing a unified data perceptualisation design theory that fosters interdisciplinary collaboration and knowledge sharing. Therefore, we conducted a meta-analysis of existing subfields and theories, considering both current practices and future visions. To address current shortcomings in defining and documenting related work—issues that hinder accessibility—we present several contributions, including a refined definition of encoding channels, a data perceptualisation pipeline and a conceptual model for representing multisensory data mappings that accounts for situatedness, interaction style, intention and multisensory experience.

CCS Concepts

• **Human-centered computing** → *Visualization design and evaluation methods*; **Empirical studies in visualization**; *Displays and imagers*; *Sound-based input / output*; *Haptic devices*; **Interface design prototyping**; **User interface design**; *Contextual design*; *User centered design*; *Visualization.*

Keywords

Data perceptualisation, unified theory, human-information interaction, multisensory interaction, data physicalisation

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1 Introduction

With *The Semiology of Graphics* [3], Jacques Bertin created a foundation for research on how data is efficiently visually presented to humans by introducing a model for representing relations between primitive components of an image and human vision, and related design guidelines. Multiple extensions and adaptations of his theory have been developed for other senses and interfaces, but they require consideration of additional aspects that could previously be overlooked when limiting the scope to static images, such as interaction and multisensory processing. In this paper, we investigate a theory exploring how data is efficiently presented to a human through any of the senses via arbitrary interfaces, a concept referred to as *data perceptualisation* since the 1990s [11, 32]. Although the term has surfaced in a handful of works exploring multisensory interfaces or opportunities for interdisciplinary knowledge exchange [13, 29, 35, 38, 58], there remains a lack of formal definitions, frameworks and resources to be shared among the disciplines involved in designing artefacts for data presentation. Today, many findings and resources remain scattered across disciplines and are challenging to combine.

Data perceptualisation represents a largely untapped common ground across fields such as visualisation, sonification, haptification and multisensory interaction, offering opportunities to share concepts, methods and theoretical insights that are often developed in parallel. We suggest that one factor limiting knowledge exchange are the subtle yet important differences in the ways concepts and terminology are understood and used across domains. By making common terminology and design principles explicit while respecting the distinct realities of each domain, a unifying and accessible theory could help address shared challenges in design and evaluation, reduce duplication of effort, and support the development of approaches that align more efficiently with the inherently multisensory nature of human perception. Without such integration, knowledge exchange between fields focused on interface design as well as perception remains difficult, increasing the risk that established lessons are overlooked and that theoretical findings are misapplied, potentially leading to ineffective or even harmful outcomes [28].

In this paper, we establish a data perceptualisation design theory (DPDT), demonstrate the potential and challenges of introducing such a design theory in practice, and propose concrete solutions to make the theory unifying and accessible. We begin by defining data perceptualisation and presenting examples of perceptualisation artefacts, along with a motivation for a shared theory, in Section 2. The definition of a data perceptualisation design theory, its practical applications and its core components are further elaborated in Section 3, along with multiple suggestions for what to strive for. In Section 4, we present three solutions that address current challenges holding back unification and effective knowledge sharing across subfields such as visualisation, sonification or data physicalisation. The first challenge concerns inconsistencies in how marks

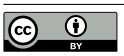

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Table 1: Clarifications of terminology used in this work

Term	Definition adopted or refined (marked with *) for the domain of data perceptualisation
*data perceptualisation**	An artefact presenting data to a user with the aim of providing objective insights of the data, using any display device or sensory modality. Note that the term may also be used to refer to the related design practice and research domain. See Section 2.
design theory	A theory concerned with the design of an artefact. See Section 3.
data attribute	A measurable property represented through a variable or dimension in a dataset, such as a column in a table [63].
*mark**	Examples of marks include a dot, sound and air burst. A mark is the phenomenological structure that acts as the design element encoding data in the data perceptualisation artefact, and whose properties are decoded through various interactions, such as watching, listening, tapping or stroking. We suggest that the mark be used to indicate which stimuli belong together according to the human observer's point of view. See Section 4.2.
*channel**	A perceivable property of a mark that can be varied to create a scale of experiences. Examples include colour, roughness or the intensity of a rain sound. In this work, we use and encourage this term to refer to the full chain created by an encoding channel, a physical phenomenon and the human experience of it. See Section 4.4.2
*encoding channel**	Refers only to the objective instruction used for controlling display devices, clarifying how a data attribute is encoded into the physical external representation. See Section 4.4.2
data mapping	The matching of data attributes to encoding channels, which is one of the important design decisions made in data perceptualisation.
idiom	An established type of design solution, for example a pie chart [63]. Defines how data transformations, marks and supporting design elements can be reused with different data.
external representation	Defined by Fox and Hollan as "*the form of information, purposefully encoded as structures in material artefacts that serve a semiotic function as part of an interpretive process*" [29]. Examples include text and data perceptualisation artefacts.
*display device**	A device designed to create an external representation, used for transforming data to a physical format. Examples include monitors, speakers and actuators. While many of these are electronic, manufactured physical objects, such as printed images and static physical objects, may play the same role and are also covered by this definition.
situatedness	Describes how information is integrated into its surrounding environment, usually as a relation to a user, item or event [2, 8].
multisensory	Used here to clarify that a human combines multiple sensory experiences, sometimes from different sensory modalities. Often used interchangeably with the term multimodal.
multimodal	Used when describing a system using multiple input or output channels.

and channels are conceptualised across fields. We address this by treating a mark as a conceptual and interactive construct, and by drawing a more explicit distinction between full channels that span from data to experience, and encoding channels that define how display devices are controlled. The second challenge is the current lack of a unified framework to express the various perceptualisation artefacts, which is necessary to enable efficient interdisciplinary knowledge sharing and artefact comparison. We present a perceptualisation pipeline and a complementary conceptual model for representing artefacts, drawing on concepts from multiple existing models. Compared to most existing models, it aims to highlight only the essential aspects of expressing the relation between design elements, while avoiding the details added under the assumption of a specific sensory modality or use case. Our model further includes situatedness, intention, interaction and targeted experiences. For less standardised interfaces and comparisons across various setups, it is essential but challenging to clearly incorporate these aspects into existing models. By utilising a directed network with feedback loops, the presented conceptual model facilitates the expression of complex, multisensory relations and interactions while avoiding the introduction of perceptual factors that are commonly unknown to a designer. We showcase its value in use by applying it to examples of perceptualisation artefact designs. In Section 5, we discuss the potential for efficiently structuring knowledge in a database, other relevant future pursuits for the presented data perceptualisation design theory and provide some concluding remarks.

2 Data Perceptualisation

In this section, we gather definitions related to data perceptualisation to clarify its scope and key terminology. A summary of the terms and definitions we use is provided in Table 1. Many of these terms are addressed in later sections, with more detailed explanations of challenges encountered in searching for definitions and models that fit the general scope of data perceptualisation. Most of the definitions shown in Table 1 are adopted from existing work, but we propose refined clarifications for the terms *data perceptualisation, mark, channel, encoding channel* and *display device*.

2.1 Defining Data Perceptualisation

A definition of data perceptualisation must be effective as an umbrella term and, at the same time, clarify important distinctions from other artefacts made with different goals in mind. We define

a *data perceptualisation* as *an artefact presenting data to a user with the aim of providing objective insights about the data, using any display device or sensory modality*. Note that the term may also be used to refer to the related design practice and research domain. When we *perceptualise* data, we refer to the creation and use of a data perceptualisation artefact. However, this term should be used with caution, as it may be misinterpreted outside the field of data perceptualisation.

At its most fundamental level, a data perceptualisation artefact is designed to encode data within the physical world. It is assumed that the artefact, also referred to as the *external representation* [29], is intentionally decoded by a human to create a matching interpretation of the data being presented, as illustrated in Figure 1. We emphasise that perceptual and cognitive decoding is an interactive and iterative process. However, in clarifying the goal of data perceptualisation, the primary focus of data perceptualisation lies in the data-to-human-directed information flow. Similarly, on the system side, a dynamic data perceptualisation may include a feedback loop through subcomponents that respond to user interactions.

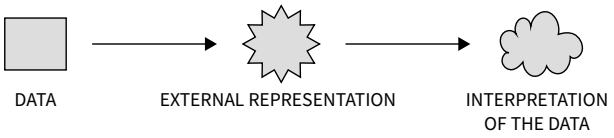

Figure 1: Data perceptualisations encode data values into an artefact in the physical reality, here referred to as external representation. These encoded values are always intended to be actively decoded by an observer, creating an interpretation of the data.

Multiple research fields are concerned with the design of data perceptualisations. Figure 2 illustrates examples of existing subfields and their shared related fields. Data perceptualisation offers a coherent scope for integrating these often-overlapping subfields, while still allowing them to distinguish themselves through specialisation in sensory modality, display type, task, target user, content or context. Without the scope of data perceptualisation, providing a description that includes all subfields and topics can be difficult, even though they share multiple similar interdisciplinary challenges and design goals. A number of existing fields offer a similar overarching scope. An example is immersive analytics [61], which may be seen as data perceptualisation with a focus narrowed towards Extended Reality (XR) solutions for data analysis. Another example is data sensification, which encompasses data representations that "*deliberately aim to reveal insight through any sensory modality*" [37]. For data sensification, the focus is on artefacts that are part of the environment and designed with respect to contextually relevant metaphors, which often relies on the human designer's sensibility for storytelling rather than on theory of the perception of abstract data dimensions. What is encompassed as insight from data may include more qualitative and subjective interpretations, opening the definition to include data art. This conflicts somewhat with fields such as sonification and information visualisation, where the definition is much more strictly limiting the design of artefacts to strive for objective and reproducible data interpretations.

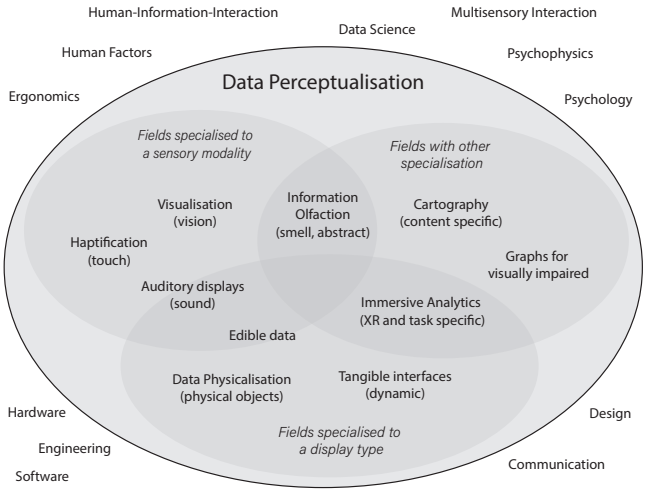

Figure 2: Data Perceptualisation as a research domain encompasses multiple subfields concerned with the design of data-presenting artefacts and provides a suitable research framework for exploring interdisciplinary knowledge exchange among them.

We suggest that this stricter scope be adopted in data perceptualisation, as it offers multiple specialised methodologies and metrics that are better suited to efficient exchange across specialised fields. Nevertheless, multisensory experiences are often more easily comprehended through metaphor, making it valuable to incorporate perspectives and methods from data sensification. Research on multisensory interaction and integration naturally overlaps with research on data perceptualisation, where the interaction with artefacts provides a means of exploring human abilities. Data perceptualisation, by contrast, primarily aims to explore the design of artefacts and resources that support their creation.

Important design qualities that data perceptualisations strive for include making the interpretation of the encoded data predictable, accurate and similar across users, rather than providing arbitrary experiences. In this context, aesthetic quality refers to the artefact being read efficiently, confidently and comfortably, leading to a pleasant experience rather than being described as beautiful. The subfields tend to emphasise a user- and task-driven design approach for creating and evaluating data perceptualisation artefacts. A well-designed perceptualisation artefact helps users with a specific task, alongside a sufficiently accurate interpretation of data values. Users and context shape how the same physical artefact is interpreted, making it essential to define and study data perceptualisations through well-documented and replicable studies across varying contexts. This builds on the foundations of data-driven approaches, which focus on defining which design solutions and perceptual abilities are compatible with different data characteristics.

2.2 Examples of Data Perceptualisation and Differences Between Subfields

There are multiple important differences between subfields, making it challenging to define a consistent theory. In cartography and

visualisation, *The Semiology of Graphics* [3] introduced a systematic matching between a *data attribute*, such as a column in a table dataset, and a physical property that can be perceived in isolation. Bertin referred to these properties as *visual variables* or *retinal variables*, which correspond to specific primitives of visual perception. In modern information visualisation, a widely utilised theory is that of Munzner [63], in which the variable concept is referred to as a *channel*. A simple example of mapping data attributes to channels in a scatterplot, which is one of the options suitable for the data-analytic task of obtaining an overview, is illustrated in Figure 3. Information visualisation design theory helps inform both the choice of idiom and the selection of a channel for mapping each data dimension.

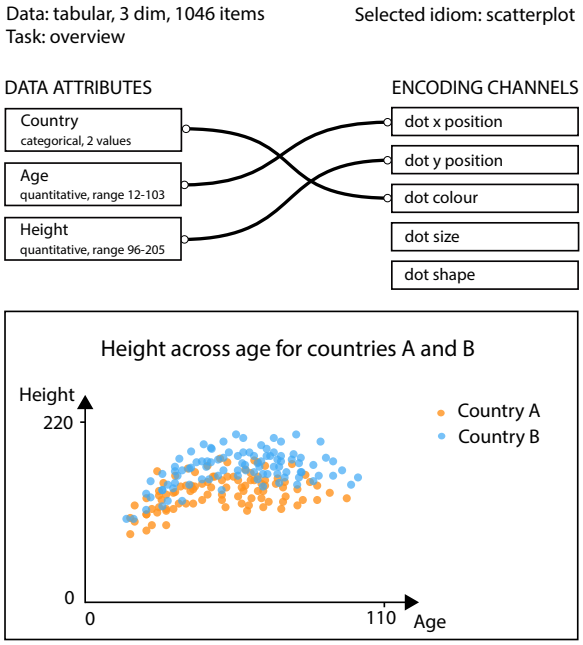

Figure 3: Simple scatterplot visualisation example illustrating the mapping between data and encoding channels that control a dot's properties

A similar method for presenting data through sound is Parameter Mapping Sonification (PMSon) [33], where non-verbal *sound synthesis parameters* can be viewed as auditory channels. These can vary in terms of sound characteristics, temporal variations or the location of the sound source. While early research on auditory channels primarily focused on aspects easily defined for synthetic sound waves, alternatives using sounds that humans have naturally evolved to notice in their environment have been found to be more aesthetic [21, 57, 82]. Examples include the type of instrument or the intensity of rain. This marks a key distinction from visualisation, which focuses on low-level perceptual abilities rather than on conceptual channels requiring higher-level cognitive processing to be understood. Compared to visualisation, sonification further makes a clearer distinction between the physical sound and the experienced sensation, using different terminology for the two, such as sound frequency versus pitch. The separation between physical properties and sensations is also necessary in haptics, where many channels require active exploration by users.

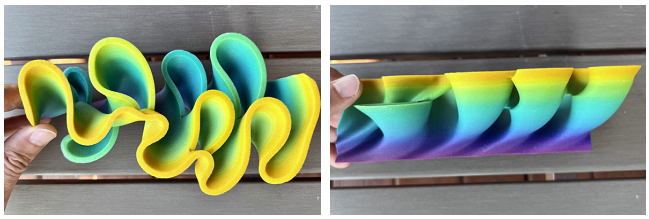

Figure 4: A static data physicalisation example by Zoltán Sylvester [18], which allows exploration of how a river's shape has changed over time. Time is encoded in the colour and layer height, with the yellow layer on top representing the most recent shape.

Data physicalisation is a field that explores how physical objects, or the interaction with them, can be used to encode data [19, 88]. Figure 4 shows an example of a data sculpture, which can be easily explored through natural interactions. Using multiple senses when observing data offers numerous benefits, such as making information more memorable and enhancing learning. With new technologies, there is an increasing number of *dynamic data physicalisations* and tangible interfaces that can adapt to different data values in real time. Although currently rather bulky, these prototypes serve as valuable tools for envisioning and researching future interface possibilities [44]. Multisensory Extended Reality (XR) solutions are interesting to compare with data physicalisations, as they often create simulated experiences of physical objects. For example, a user might be able to "touch" objects in a virtual 3D environment by using ultrasound to create a haptic experience in the palm of a hand [5]. Even though both physical and virtual objects in the examples may encode a data attribute with colour, they use different means of creating the stimuli, and rather than letting users touch a physical object, the XR display device creates an illusion of touching an object. While creating illusions beyond 3D screens is uncommon in visualisation, it has been explored and applied to other senses. For example, headphones can simulate the apparent location of a sound (virtual surround sound).

2.3 The Pursuit for a Shared Design Theory

When attempting to represent physical and simulated examples within a single framework for expressing mapping choices, fundamental differences must be addressed. The artefacts are interacted with in distinct ways, and the theoretical models and terminology vary across fields, complicating direct comparison. Using details needed in a model for a different modality can prompt reflection on previously overlooked aspects. However, it may also introduce aspects that seem irrelevant or challenging to include and name. We further discuss this challenge in Section 4.4, where we present a framework for the general case of data perceptualisation.

Striving towards a multisensory theory is not only relevant for immersive analytics and data perceptualisation, but has also been advocated in the fields of sonification [35] and visualisation [29]. This interest is driven by a growing recognition of the complexity

and subjectivity involved in the decoding stage of the perceptualisation pipeline, and by calls to study this process more strategically. Cooperation between research communities has been identified as essential for developing a cohesive and applicable design theory for advanced human-information interaction interfaces [22, 29]. Initial efforts to bridge the gap between visualisation and psychology research have already been proposed by Fox and Hollan [29] and there are multiple works on multisensory design theory from various perspectives [38, 41, 61, 65, 66, 71] to combine and build upon. By providing a more explicit common ground, multisensory models and vocabulary, data perceptualisation has the potential to unify concepts and promote knowledge sharing across additional research communities concerned with the design and experience of artefacts that present data to humans.

As further illustrated in the next section, the design and creation of a data perceptualisation depends on resources and considerations from many different disciplines, such as engineering, psychophysics, ergonomics and user experience. To create a "good" artefact, it is necessary that all considerations are met and that support is available for the many steps of the design process. This emphasises the need to explore how these interrelated fields can cooperate efficiently, which we believe is one of the most promising and valuable contributions to pursue within data perceptualisation. Rather than expecting shared abstract models and definitions to outperform specialised ones in practice, data perceptualisation can be seen as providing a complementary layer for inspiration, interdisciplinary knowledge exchange and support for coevolution. One could even argue that contributions to data perceptualisation should be developed with this perspective in mind. The field can target the direct need for resources to share knowledge and a shared design theory that clarifies which knowledge is helpful for designing artefacts and how to structure this knowledge.

3 Data Perceptualisation Design Theory

A design theory is a resource that supports creators in "how to do something", and it can relate to the process of ideating, creating or reusing a solution. The theory resource relies on efficient means of acquiring, documenting and sharing knowledge. Common characteristics of design theories include that they inform on abstract concepts [56, 113] and solutions that can only be optimised to specific contexts rather than a uniform truth. Hence, much of the reusable knowledge on solutions is contained in the artefacts themselves [15]. Essential components for efficiently communicating information system design theory, synthesised by Gregor and Jones [30], have previously been used to inspect sonification design theory [64] and are useful for guiding the development of a data perceptualisation design theory (DPDT).

In this section, we present our efforts to establish a DPDT by bringing together content and use cases from related fields to define what DPDT entails. Systematic methodologies risked holding back the scope too much. Instead, we adopted a more open but more extensive exploration of works, allowing for the inclusion of a wider variety of perspectives and considerations. Relevant aspects encountered from various contexts have been thematically clustered to derive the summarising lists and tables presented in this section. We also share more overarching observations and insights on what is currently lacking and what is possible to support in practice.

3.1 Users

The DPDT is created and accessed by humans, machines or both, in a wide variety of cases. Different hardware, algorithms and applications, as well as different groups of humans, engage with the theory with different goals in mind. We identify two general groups of human users that frequently create perceptualisation artefacts or resources and benefit from direct or indirect contact with the theory. The first group is *perceptualisation experts*, such as researchers, engineers and designers. They often develop resources and knowledge shared within their own community, while the perceptualisation artefacts, creation tools and hardware they develop are designed and evaluated with different end users in mind. The second user group consists of *domain-specific users* who are interested in exploring, analysing or presenting their own datasets. They have domain-specific knowledge and needs related to the data, and often co-create their perceptualisations with the help of a specialised tool or a perceptualisation expert. An important characteristic is that, as end users, this group tends to consume the perceptualisation more than once and often prefers a solution that is useful after some learning phase. Both perceptualisation experts and domain-specific users may be interested in creating a perceptualisation for *general-audience users*, typically to tell a story. These solutions are designed to be intuitive and beneficial, with consideration of the audience's demographic differences. It is further common to design with the goal of creating an enjoyable, educational or memorable experience. The majority of general-audience users are not personally involved in the creation process and experience the perceptualisations without prior knowledge of exhibitions, presentations or other media. Rather than being users of the DPDT, the theory includes artefacts and studies made with them in mind.

3.2 Common Steps to Support

The primary goal of a DPDT is to support users who design data perceptualisations or conduct related research studies. Such users must address multiple subtasks and progress through several iterations within a design process. By exploring common design practices, available tools and brainstorming visionary scenarios, we identified eleven tasks that are supported by a set of complementary resources and user interfaces:

- General introduction to the design theory and community resources, supporting novice practitioners in their path to data perceptualisation expertise.
- Comparison of design practices and resources to structure and realise a project.
- Explore the problem by gathering information on the end users' preferences and tasks, or identify a knowledge gap to study. Define relevant facts and preferences regarding how the data should be presented and interacted with.
- Prepare a dataset to display, as well as its metadata relevant for making design decisions.
- Initialise hardware, identify its properties and customise it for the end user.
- Explore related existing perceptualisations, findings from their evaluations or other case-related design theory.
- Identify and exclude design solutions that are not suitable and explore and compare multiple design alternatives.

- Test run and fine tune a selected solution (prototype) in iterations as rapidly as possible.
- Evaluate solutions using an appropriate method.
- Create and run final solutions for end users.
- Export information about the solution for publications or inclusion in a database.

Some of these functionalities further rely on access to a system for recommending solutions, an engine for efficient data rendering and querying, or databases that store design theory in formats readable by humans or algorithms.

Perceptualisation creators have to solve multiple of the listed tasks throughout their project, regardless of which sensory modalities they design for or research. This creates dependencies on different experts and may slow down the process, and often multiple individuals work in parallel to solve this larger interdisciplinary challenge [86]. To the best of our knowledge, no existing solution includes all of the listed functionalities and striving for a one-size-fits-all solution is not well motivated. Depending on who uses the system and for what purpose, each interface should be tailored to strike a good balance between simplicity for the specific case and flexibility [74]. Instead, a more suitable approach to data perceptualisation and its subfields is to increase the possibility of combining complementary resources, as for instance seen in the standardisation of cartographic data formats.

3.3 Example Applications

To get an idea of how DPDT can be used, it is interesting to consider how design theory is used in practice in the subfields of data perceptualisation today. In the following, we discuss examples of solutions that directly support the selection of a good perceptualisation design. This is challenging as the rules and guidelines for choosing appropriate mappings are complex and numerous. Also, for experienced designers and researchers, it is unrealistic to know them all by heart. Selecting an inappropriate perceptualisation design poses a high risk of misinforming users and, in the worst case, producing dangerous outcomes when decisions are based on the incorrect interpretation of data. Visualisation Recommendation Systems (VRSs) are increasingly supporting perceptualisation experts and domain-specific users in exploring suitable solutions. *The Grammar of Graphics* [103] is a foundational work in the creation of visualisation recommendation algorithms. Given a dataset, automatic graph generation is enabled by defining established design knowledge as grammar rules. Using the grammar ensures that a mapping is correct and that exploring multiple alternative solutions becomes easier. Recommendation systems for information visualisation and cartography that build on the grammar have since been advancing rapidly and recommendations now consider additional factors and support additional types of graphs in a variety of graphical interfaces [42, 43, 48, 75, 104, 107, 108]. Regardless of the approach, all automated VRSs face the challenge of effectively combining existing knowledge to inform their recommendations, as well as updating this knowledge when new information becomes available [52, 106, 107]. Notably, many existing recommendation systems do not refer to the studies that inform their algorithms or rely on limited and potentially outdated studies [75, 105, 106] even though accuracy and transparency are essential qualities of these algorithms.

It is worth noting that VRSs do not claim to provide a single perfect answer, and most tools allow users to adjust the recommended solution or select among options. An interesting approach in ggplot2 [101] is to deliberately violate design guidelines by offering a "bad" choice for the number of subintervals (bins) in a histogram. This nudges users to search for a better customisation that fits their data. Considering the overarching goal of gaining insight from data, this approach to adjustment may be more effective than pursuing an optimal choice. The purpose of visual recommendation systems is not to replace human reasoning or artistic expression, but to support and augment them. Human-in-the-loop solutions enable designers to explore alternatives, make informed choices and justify design decisions through iterative processes. They allow space for situational context, nuanced interpretation and complex metaphors that remain beyond the reach of algorithmic reasoning. In practice, Data Physicalisation Design Theory is not only made accessible through guidelines and related literature, but is also embedded directly into design tools themselves, such as in the form of reusable design patterns [81, 95] and the features that prototyping tools provide or explicitly disable.

3.4 Theory Resources

Like all design theories, DPDT focuses on specific aspects. There are also related contributions that help structure and evolve the collection. We have identified the following high-level categories of knowledge contributions and resources that a data perceptualisation research community might provide:

- *Perceptualisation artefacts* made to present data in real use cases. It may also include reusable design patterns, idioms and encoding channels.
- *Study results*, of which multiple subtypes may be found based on the quality they measure.
- *Design advice* which includes guidelines, design claims, design spaces, frameworks and more informal advice that help inform the design choice in a way readable to humans.
- *Design process advice* provided as methods or guidelines in a way readable to humans. Evaluation methods can be seen as an important subtype of this category.
- *Implementation resources* such as prototyping tools, conceptual models like pipelines, software and hardware.
- *Recommendation system resources* such as grammar rules, training datasets and algorithms. These machine-readable contributions can be linked to study results and design advice contributions to enhance transparency.
- *Literature* or other informational resources that provide an introduction, summary or extended description on a topic.
- *Theory definition and refinement* such as standardisation, unification and vocabulary. We also include explicitly identified research gaps in this category.
- *Communication resources* such as research community webpages, artefact galleries and venues for publication or networking.

Multiple qualities can be studied, and below we present an overview and comment on two larger categories that we identified: (1) knowledge that informs the performance of the encoding solutions and (2) knowledge that helps explain how the decoding functions. The tables below provide a more comprehensive overview of these measurable qualities than existing work. However, they are likely still incomplete, merit further refinement and include some items that are difficult to categorise as uniquely informing encoding or decoding. An important and related consideration is that all empirical study results can vary in aspects such as the specific display device used [9], between individuals, across environments and the task a user intends to solve. To efficiently find and compare perceptualisation artefacts and related knowledge, it is essential to provide sufficient details about the setup and, potentially, additional information on users' characteristics, their tasks and context. Without replicating studies, we cannot be sure how generalisable and applicable they are across different contexts. It is essential that DPDT includes systematic evaluation methods and creates means to efficiently synthesise and apply complementary studies.

3.4.1 Theory Informing the Encoding. The theory most relevant to informing specific encodings is generally concerned with "*what works and how well?*" and is presented in a way that makes it easy to use in an application. Instead of formulating rules and guidelines based on guesses about perceptual characteristics, designers and recommendation systems benefit from referring to comparative studies of what actually works best in practice for a specific case. Speculating about why something works, such as whether pie charts are primarily perceived by comparing angles or by area, does not always help motivate our decision about what to use [53]. There are multiple methods for evaluating perceptualisation artefacts and channels [7, 50, 63, 77, 84, 100, 101, 110]. Evaluation methods are undergoing continuous development, and a growing body of work proposes complementary or refined frameworks and tools to simplify the process and improve the validity and comparability of studies [24, 29, 34, 54, 91]. An overview of measurable qualities is provided in Table 2.

The data perceptualisation design choice is informed by multiple works that define the characteristics and performance of different channels and their combinations. Measuring confidence and other user experiences can be as important as the accuracy, since an annoyed or uncertain user is likely to reject the solution altogether. The applicable details provided by studies that inform encoding design differ from those provided by studies on decoding. For example, the full hearing range of sound pitch ranges from 20 Hz to 20 kHz, but it has been recommended that interfaces should limit it to the MIDI notes 35 to 100 (≈61Hz–2.6kHz) [10]. Trained listeners can discriminate and identify pitches more accurately than untrained listeners. For expert listeners, the mean error in noticing a pitch change was measured to be 8% for a 5% pitch change, whereas novice listeners had a mean error of 23% for the same change [68]. A pitch change of at least 10% is suggested for general use.

A challenge in summarising the findings is that knowledge comes in various formats, such as qualitative results, design guidelines, and reusable successful designs, including idioms, design patterns and implementation resources. For example, colour spaces and the BARK scale for sound loudness can be used to present values in a way that end users experience as a uniform scale. While their design is informed by perceptual sensitivity, they ultimately help define what works and apply that knowledge efficiently as reusable solutions.

Table 2: Overview of aspects informing the encoding

Characteristics of encoding channels or idioms
Clear definition of how it is created and interacted with [6]
Supported level of organisation (scale type) [3, 31, 94]
Task suitability [48, 63]
(Un)suitable channel combinations
Recommended range of stimuli [10, 90]
Recommended channel length (information transfer) [3, 9, 50, 67]
Related semantic metaphors, scale polarity and emotions [20, 70, 98]
Uniform scales and other successful and reusable design patterns
Design spaces, marks, frameworks and strategies [16, 62, 73, 83, 89]
Performance
Accuracy, error rate, task completeness, information retention [7, 100]
Pairwise comparisons [76, 105]
Derived rankings for specific types of tasks and data [78]
User confidence in reading the values [29, 47]
User acceptance and comfort [23, 67]
Other user experience- and usability-related findings
Environmental impact and sustainability [40]
Price and quality of available hardware and software [55, 86]

3.4.2 Theory on How Decoding Takes Place. The theory that helps explain why and how a design works is primarily concerned with decoding and identifying generalisable characteristics of the human body and mind. In the optimal case, psychophysical, ergonomic and cognitive studies should be replicated and reported with percentiles to assess individual and demographic differences. An overview of aspects that inform the decoding of data perceptualisations is provided in Table 3.

Table 3: Overview of aspects informing the decoding

Psychophysical characteristics
Absolute threshold and point of subjective equality (PSE) [50]
Sensitivity curves, e.g. equal-loudness contour and luminosity function
Difference threshold, e.g. just noticeable difference (JND) [50]
Stevens's power law exponent and Weber fraction, if applicable [50]
Applicable range for scaling laws (e.g. Weber fraction)
Channel capacity for information transfer and information rate [50]
Temporal characteristics of the stimuli [49]
Relations and interference from other stimuli or factors [49, 112]
Gestalt characteristics [13, 92]
Details related to the sense organs and interaction
Receptor type, locations and characteristics [12, 50, 110]
Interaction requirements, such as active or sequential exploration [50]
Ergonomics and human factors
Models of multisensory processing [22]

There is widespread and well-motivated scepticism about the generalisability and usefulness of psychophysical studies for informing

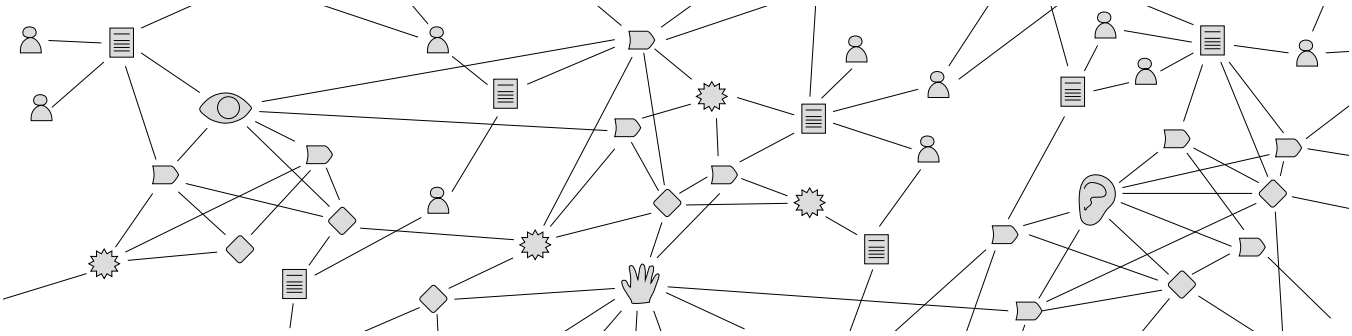

Figure 5: A knowledge graph database can represent complexly linked data items, as shown in the image, by storing information in nodes of various types (such as sensory modalities, channels, publications, authors and artefacts) and their relations.

the design of data perceptualisations. One of the values the theory on the decoding process can provide is an understanding of the foundations necessary for efficiently ideating new solutions. It can, for example, help to identify designs of encoding channels or hardware that best suit perceptual requirements or are likely to be misinterpreted. General human factors and ergonomics principles also help prevent designs that are likely to be discriminatory or cause long-term harm, which can be challenging to identify during an interface usability evaluation. These facts help formulate empirically motivated design rules, but will sometimes be context dependent, making it relevant to access study results and design rules together.

Traditionally, perception has not been studied with data perceptualisation in mind, but rather with perceptually optimal experimental setups [110]. For example, the *absolute threshold* is a measure of the intensity at which a stimulus is noticed at a rate of 50%, not a practical lower limit for data perceptualisation. Relevant applicable details, such as the range of stimuli most suitable for expressing data values, may be difficult to locate because they have not been documented as interesting facts. The theory may also be difficult to read and use for those unfamiliar with the jargon and metrics used. For example, the distinction between fast- and slow-adapting receptors is not clearly understood with respect to the types of stimuli they respond to. When conducting studies on perception, one must consider multiple challenging aspects, such as temporal factors, inter-channel relations, perceptual sensitivity that adapts to prior stimuli, and differences between increasing and decreasing stimulus intensity. It is also possible to conduct studies that consider varying contexts, individual differences and the learning processes that may occur during an experiment. To make applicable knowledge easier to locate in the future, we believe the field of data perceptualisation needs to further clarify which aspects it considers relevant and why. It must also support the creation of these studies, making the methods and supporting tools adapted for efficient use in data perceptualisation. Fortunately, there are already a few works proposing methodologies specifically adapted to visualisation [24], haptics [50, 110] and sonification [112]. The development of additional supporting frameworks and tools, and increased consideration of context from the field of psychophysics [102], could improve both the quality and quantity of studies informing perceptualisation design.

3.5 Accessibility and Evolution

To advance the theory, researchers need to further review relevant publications, identify research gaps and conduct studies that follow a recommended methodology. Novice researchers are a particularly interesting group to consider for resources that introduce the basics and enable access to the state of the art. Parsons suggests that the field of visualisation can take inspiration from other design fields in how they educate students [72], with motivations that would also apply to perceptualisation. Rather than being expected to read extensive literature before starting, students learn by doing with the help of context-relevant advice. There is a clear need to explore solutions to inform novice researchers and designers, as evidenced by reports of repeated mistakes and designs that contradict well-established design theory [28]. There is also criticism about scientific publications lacking sufficient detail, emphasising the need for further guidance and standardisation [54, 79].

Interviews with practitioners from haptics [86], sonification [57, 79] and data physicalisation [85] highlighted multiple challenges arising from limited access to relevant information, prototyping tools and interdisciplinary expertise. A design solution must be selected through a combination of contextual, aesthetic, practical, economical, ethical and ergonomic perspectives [1, 40]. Practitioners emphasise the value of exploring similar artefacts as part of the design process, and multiple research communities have created webpages to present galleries of artefacts, such as sonification.design[1] and dataphys.org[2]. Design theory in the form of study results remains limited and difficult to find. Zeng and Battle [105] recently presented a collation of knowledge on graphic perception that helps inform visualisation recommendation algorithms, but is limited to the standardised, well-documented case of static 2D graphs of tabular data. Today, the interdisciplinary design theory underpinning data perceptualisation is dispersed across multiple domains, whose subfields tend to evolve independently and in parallel rather than as part of a shared intellectual community. A specialised venue is missing and, unfortunately, valuable replication studies have been observed to be rejected as not novel enough even in some venues that explicitly encourage these contributions [29, 52, 54, 105]. It hinders the evolution of the theory and further disperses related studies, likely making them harder to

[1] https://sonification.design
[2] https://dataphys.org

locate and cross-reference. Introducing a new journal or conference is unlikely to solve all these challenges and research communities would likely benefit from additional means to share knowledge between many specialised fields. Similar observations have been made in the field of haptics [69], where researchers have increasingly begun to examine the challenges and requirements of creating trustworthy community resources that enable meaningful contributions from individuals without extensive domain expertise.

A positive example to draw inspiration from is the field of cartography, which in recent years has established standardised data formats and query languages, thereby making case-specific knowledge more reusable and accessible [17, 99]. It makes it easier for their community to build solutions that complement one another and collectively expand the collection of knowledge, which is likely to have a positive impact on the evolution of the research field [39]. One of the solutions used in cartography and for other design theories [43, 56, 113] is linked data or knowledge graphs, as illustrated in the example in Figure 5. Knowledge graphs provide an efficient and flexible way to represent and explore data with complex relations [36], making them interesting for context-dependent design solutions. Before such a resource can be made available for data perceptualisation, the precise concepts to include and their format need to be formally defined. The potential of storing data in nodes and relations of different types, as realised in knowledge graphs, has also inspired the design of our conceptual model presented in Section 4.4.

4 Definitions and Conceptual Model for Data Perceptualisation

In this section, we introduce multiple contributions specifically developed for data perceptualisation to address key shortcomings that hinder effective knowledge exchange across research communities. Two core concepts adopted from visualisation theory to other data perceptualisation subfields are *marks* and *channels*. However, a close examination of their treatment in existing theory reveals several important inconsistencies. These issues must be resolved before introducing the shared models presented in Section 4.3 and Section 4.4, both of which fundamentally rely on the concept of markers and channels.

4.1 Defining Channels

At a general level, a channel is a well-defined concept that is consistently used across all subfields we examined. In particular, the sonification literature articulates a set of properties that channels are expected to satisfy, many of which are directly applicable to data perceptualisation [79, 112]. Accordingly, channels are generally expected to:

- reflect objective properties or relations to the input data. This means that, to an acceptable level, they should exhibit a linear relation between stimuli and sensation. The sensation should be largely the same regardless of the prior stimuli, indicating that the channel is not exhibiting hysteresis effects.
- exhibit little perceptual interference with other channels
- have a sufficiently high perceptual resolution
- be reproducible and usable repeatedly with different or identical data
- be consistently understood in the same way by multiple individuals

Given that many artefacts are ultimately rejected by reluctant users [20, 67], we propose an additional requirement that channels must be acceptable to users. It is important to note that what constitutes a "sufficient level" of acceptance may vary across contexts. For example, some users may become more open or develop improved interpretative skills through training. Nevertheless, at a general level, channels should adhere strictly to these requirements, even when practical solutions rely on countermeasures for non-linear perceptual effects or interference between channels. In practice, channels are rarely used in isolation. Instead, channels are typically combined and balanced in groups [9, 111]. As a result, these rules are more appropriately applied to each channel as it is presented alongside others within an interface, rather than assuming that all channels function as isolated, universally orthogonal and reusable primitives.

4.1.1 Different terminology across fields. While a list of requirements can be defined for the concept of channels, an obvious challenge is the lack of a standardised vocabulary. Often, a domain-specific term is combined with *channels*, *variables* or *parameters*, which complicates cross-referencing and term selection. Multiple versions suitable for a more general multisensory scope have been suggested, such as *encoding variables* [80], *perceptual variables* and *sensorial channels* together with *sensorial variables* [61]. Still, these terms have only been partially clarified. We are not the first to point out that intuitive meaning and emphasis that fit local scopes often shape the suggested terminology and definitions [14, 41, 46].

4.1.2 Poorly defined exact nature of channels. A central aspect of the traditional definition of channels in visualisation is their treatment as primitive properties of a *visual mark*, such as a dot or line, that match pre-attentive perceptual attributes [60]. This allows for a seemingly automatic one-to-one mapping of the encoding instruction, physical phenomena and final experience that together span the full chain illustrated earlier in Figure 1. Channels in other sensory modalities are often multisensory, conceptual and mediated through active human interaction unfolding over extended time spans, rather than being perceived instantaneously or passively [46, 51]. A final experience is not as unimodal as one might think, and can even be impacted by intention and conceptual expectations [92]. This makes the nature of a channel less defined for domains other than visualisation.

The details that have been considered intuitive and relevant to designing artefacts have differed across sub-fields, making their concepts of the channel more focused on specific parts of the full chain. In contrast, other parts remain difficult to explain intuitively within their respective scopes. In data physicalisation, for instance, concepts analogous to channels are often referred to as *physical variables*. When these are used to describe properties such as surface colour, texture or elevation, the term is intuitively understood as referring to physical attributes of an artefact rather than to the instructions that generate it or to the multisensory experiences it affords. It takes a moment to clarify what constitutes a "smooth" surface and how to create it. The final experience is intuitive and subjective and by nature, making it hard to define or measure precisely.

The simulated sound location is also easy to explain conceptually, but must be further explained through the specific changes made to the sound wave to create the illusion. Arbitrarily using a term that can sometimes refer to either a specific part of a channel or the whole channel is bound to create conceptual confusion.

4.1.3 Challenges in naming channels. In sonification, a distinction is made between physical phenomena and the related sensations, using different terms for the two; sound frequency is not the same as perceived pitch. A physical, conceptual, sensual experience often shapes the name of the channels, but naming the three separately is rarely intuitive. In visualisation, we would want to use the same term for all three, and many haptic experiences lack everyday vocabulary to describe sensations related to a channel [70]. When experiencing a modulated vibrotactile signal, participants have verbalised the sensation as a "roughness", but not all would agree with it as an intuitive name [9]. Roughness can also be viewed as a surface property, perceptible through touch or vision. As they are related in terms of sensational and physical context, it is not necessarily a bad thing that they share the same name. It does, however, create a need for information to be structured in a way that avoids misinterpretation in a design theory resource.

4.1.4 Channels are both practical solutions and abstract concepts. In design theory, we must consider channels from a practical standpoint. One of their roles in data perceptualisation is to represent reusable and predictable solutions for information transfer. This requires some level of control over the output and experience, but at the same time, display devices have physical limitations, and designers can only instruct, nudge or train the users to perform as intended. This limitation is emphasised in *The Grammar of Graphics* [103] and motivates its use of *aesthetical attributes*, which are case-specific encoding instructions that are possible to define objectively. In design theory, where we aim to support the reuse of solutions, this has important practical value. A similar emphasis on control is evident in parameter-mapping sonification and in Munzer's [63] definition of a *channel*, which is more widely adopted and used similarly in practice. The channel concept, with a definition focused on the encoding instruction, can be used to explain solutions that account for the required interaction and time essential to other senses. However, as a coded instruction, it still risks missing parts beyond the display devices, such as situatedness, context and user intention, which are relevant to understanding and discussing the full channel and design solution. Using only the encoding-focused definition, it becomes difficult to explain how two completely separate channels could produce the same subjective experience.

Another important practical value of the channel concept lies in its ability to specify which types of data a channel is suitable for encoding [31, 83, 93], which other channels it should not be combined with, which Gestalt principles apply to it [13] and channel performance comparisons [21, 76, 78, 105]. Here, channels are understood in a more abstract sense to enable the grouping of related studies. This includes consideration of fully linked channels, allowing the incorporation of "generalisable" findings on human decoding processes that underpin many design rules and guidelines.

4.1.5 Concluding definition suggestions. To make the definitions of channels more explicit, we suggest using the term *encoding channel* for the more specific design solution in the form of an encoding instruction, and *channel* to refer to the full data-physical-experience link used when presenting data to a human. Both of these can be useful to handle at varying levels of abstraction when comparing and accessing similar solutions. While the full channel is difficult to define precisely, we introduce a conceptual model in Section 4.4 that adds detail on the physical, interactive and mental parts of the channel, which can be explored and defined through common human-computer interaction (HCI) practices.

4.2 Defining Marks

We also suggest a different perspective and definition for marks that fits the role they play in data perceptualisation. Marks provide a helpful means of linking channels to the properties of a design element, but have proven difficult to define consistently across fields. Visual marks have an important relation to position and spatial dimensions, while sound and time have been suggested as dimensions of auditory marks [3, 25]. These dimensions cannot clearly capture sound channels related to the sound location or multisensory events. Haptic devices can offer both temporal and spatial properties in relation to either an external frame of reference or the human body. The channels each of these devices supports might also vary. For instance, properties of a physical object can be explored with one's hands, an oral tactile device can show direction [96], while a haptic icon in the shape of a button can express multiple dimensions of vibration [59]. There are many more possibilities [5, 27], and the design guidelines and related channels are likely specific to the display devices. The same is true for the marks proposed for information olfaction [73]. Among these, an *airburst* mark can be explained through its association with a physical medium, whereas a *bouquet* mark relies instead on a metaphorical understanding of how multiple smells are perceived together. Multisensory experiences of marks are often better considered metaphorically or as a concept understandable to a human. A combination of multiple display devices can be used for a single conceptual channel in XR, making hardware an unsuitable frame for defining marks and channels.

In a dataset, multiple data attributes are provided for the same objective entity, creating a multivariate data object. We suggest that the mark could be understood as a design element representing a data object and is the conceptual structure we interact with in an interface. Across the many subfields, interaction is considered an additional layer of complexity, but it is only through specific interactions with a mark that channels become perceivable. Some interactions feel more immediate, involuntary and automatic, such as seeing, hearing or feeling something on your skin. Consider that it is only by looking at a mark that we can access the visual channels [4], and only by tapping, pinching or stroking an object mark that we notice other properties enabled through those interactions. Some of these interactions can occur as instrumental manipulations [45, 109] within a graphical interface, such as through selection tools rather than direct touch. To clarify, the instrument that controls the mark's channels is conceptually distinct from the mark's physical representation. We can similarly adjust the light without touching the light source, change the volume of a surrounding sound without experiencing it as belonging to the

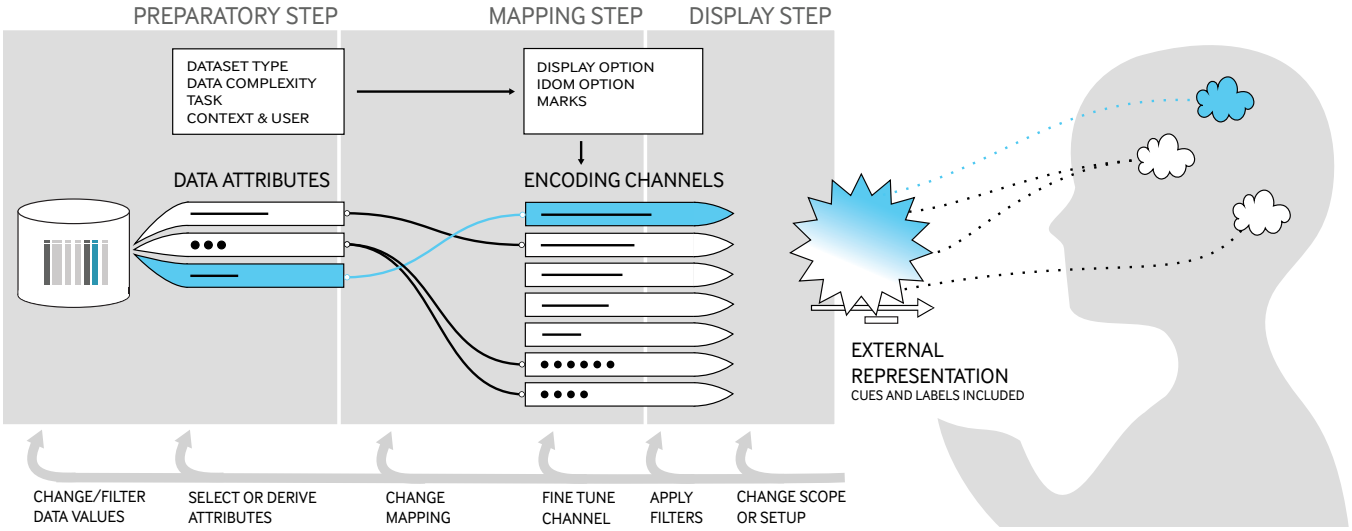

Figure 6: Perceptualisation pipeline providing an overview of key aspects in the creation and interaction of a data perceptualisation. The encoding of data in a perceptualisation is divided into a preparatory step, in which information is defined to help decide on suitable mappings, and, if needed, additional statistical or derived attributes are created. In the data mapping step, a decision is made about which of the available channels to use. While we cannot control the user's perception, the goal of a channel is to evoke a concrete experience or interpretation that is suitable for representing the data values.

physical button, or explore an object by poking it with a stick. In this way, these instruments can help activate a new perceivable layer of channels, while remaining separable from the mark.

In visualisation, marks have become closely linked to the practical expression for rendering graphical objects. However, when designing a multimodal interface, there is a need for marks to help explain which properties are understood together by the human when combining multiple display devices. Consider the example of the audiovisual SoniScope [26] idiom, which extends a scatterplot with sound. A selection tool is used to compose a sound clip containing a short sound for each marked dot. We suggest that, conceptually, it makes sense for the sound channels to belong to an audiovisual dot mark rather than a separate sound mark. By defining the mark through a human conceptual perspective, it remains possible to express glyphs, earcons, tactons and similar structures from a technical point of view and to group them, which is helpful when display devices are insufficient to explain multisensory channel relations.

4.3 Perceptualisation Pipeline

A model used in some form across all perceptualisation-related fields is the visualisation pipeline, which outlines the steps by which data is mapped to channels and displayed to the observer. It provides insights into the general design of perceptualisation artefacts, helps explain the steps implemented in the system and, in some cases, the interaction and sense-making process on the human side. Influential work with detailed coverage of the data system side and varying levels of detail on the interaction side includes the work of Munzner [63], The Grammar of Graphics [103], Parameter Mapping Sonification [33], and Jansen and Dragicevic's model for interactive visualisations beyond the desktop [45]. These tend to divide the process of encoding data into an external representation with varying levels of detail, generally into three main steps: the preparation of relevant metadata, the choice and definition of mappings and a final step in which a display device creates a physical perceptualisation artefact. There are also models that focus on the decoding that takes place on the human side. A model that captures the interactive decoding of the artefact in multiple steps is Duke's Syndetic Model [22], and the model proposed for the research program of Visualisation Psychology [29, 87] provides an abstract overview of the steps with consideration of interactive, cognitive and narrative aspects related to the field of psychology.

Keeping these models in mind, we did not find one that explicitly avoids introducing terms or concepts specific to a sensory modality while still providing a simple overview of the concepts this work focuses on. The focus lies in providing an intuitive overview of how mapping to encoding channels fits into the larger picture. In Figure 6, we present the perceptualisation pipeline in the format of an abstract data mapping example. On the system side, the general steps of data mapping are included, where each encoding channel represents a mapping choice and, by nature, serves as an instruction for controlling the display device. This instruction may further include real-time feedback to incoming data. At the bottom of the system side, we provide an overview of common influences from interactions, which are necessary both for fine tuning during the design process [33, 86] and for expressing the behaviour of a completed dynamic perceptualisation. The entire system constitutes the encoding phase, resulting in the creation of the external representation. In the pipeline, we have decided not to include additional details on the decoding process, beyond highlighting the channels that connect a data attribute, encoding channel and final targeted experience.

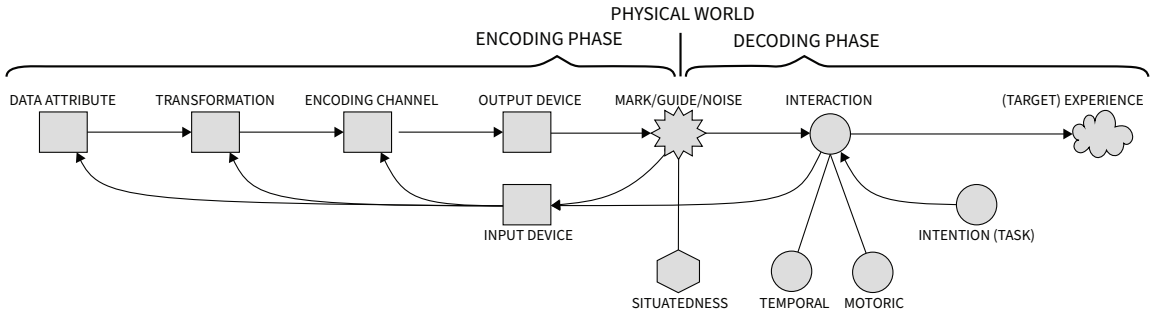

Figure 7: Conceptual model for defining and visualising the design of the data perceptualisation artefacts. Multiple nodes of the same type may exist for each artefact, creating a directed network with feedback loops rather than a single path for how a data value is encoded, displayed and explored.

4.4 Conceptual Model

As a complement to the pipeline, we present a conceptual model to capture information on a specific perceptualisation artefact design as illustrated in Figure 7. Its separable parts are complementary to one another and serve to define reusable components along the pipeline, as well as a potential context that enables comparison of artefact designs in varying and non-standardised setups. Our solution explicitly aims to provide information about the channels used in the artefact in a graph format, with each aspect represented by a node type. When representing a design, there may be none, one or multiple nodes of the same type. The conceptual model draws on multiple models presented for the pipeline, in particular the model for interactive visualisations beyond the desktop [45], which, in many steps, includes details on mappings and interactions. In a similar way to our model, it could be used to build a network to represent more complex examples. The primary difference from their model is the set of included aspects. Node types we added beyond existing models include situatedness, target experience, intention and interaction subtypes, which are particularly useful for representing the decoding process in greater detail. Some details related to rendering and interaction devices in other models have not been included, assuming that the most relevant information for informing and comparing other designs can be derived from other nodes, especially the encoding channel. Aspects that are better expressed as relevant for the full perceptualisation, such as user and context, are also not included in our conceptual model.

Starting from the left, the data attributes inform on the format and semantics of the information to be presented. Many solutions transform the data—such as deriving a single average value—rather than directly mapping to the attribute. In these cases, the transformation node will describe either the derived attribute or the method used to derive it. As in the pipeline presented above, the encoding channel represents both a choice and the specific instructions on what to display, including the response to information from input devices. While there are cases where the device acts as both input and output, most systems have dedicated hardware to handle one or the other.

We use a flexible node category to represent phenomena in physical reality that include multiple subtypes, such as physical phenomena related to marks, guiding cues, text and environmental noise that are not part of the intentionally created external representation. Through experimentation, we have found it generally useful to describe the external representation at the mark level rather than by its properties. The properties of the external representation are usually already defined in the encoding channels, making it more relevant to present what they are acting upon in the physical world. We can more intuitively define how a user interacts with a mark rather than its channels, and the group of channels shares the same situatedness. The situatedness nodes help define the nature of the stimuli, provide relevant details about the setup and can be used in layers, as shown in the example in the next section.

The aspects included in the decoding phase can be retrieved by simply asking the observers or observing them, as is common in DPDT evaluations. Models to explain the perceptual and cognitive systems [22] often provide value as a complement, but are measured using other methods. In the decoding phase, our model assumes that all perception occurs through some form of interaction, which is further influenced by the observer's intention. The intention is often a task, but could include more abstract higher-level goals as well. Temporal and motor characteristics can be interesting to clarify for some interactions. Finally come the experiences that form through the interactions and processing of the incoming information. While the aim of full data perceptualisation is some form of understanding, a successful encoding channel can create a specific matching target experience. A further distinction is made between experiences and target experiences, as there are cases where the target experience is a complex product of multiple sensations and cases where side effects may be experienced alongside the targeted one. To illustrate the model's use and highlight its strengths, we present several examples that are challenging to describe with existing models.

4.4.1 Histogram Idiom Example. Let us assume that we have collected the ages of 300 subjects. A common way to visualise this data is with a histogram. The encoding is complex to represent because the data is transformed into a derived data attribute before being mapped to an encoding channel. Furthermore, by placing bars next to each other, a shape emerges that allows the observer to choose between reading the height of a specific bar or a more abstract estimation of the shape, thereby adding complexity to the decoding process. The same encoding is observed differently depending on the task the observer intends to perform. Using our conceptual

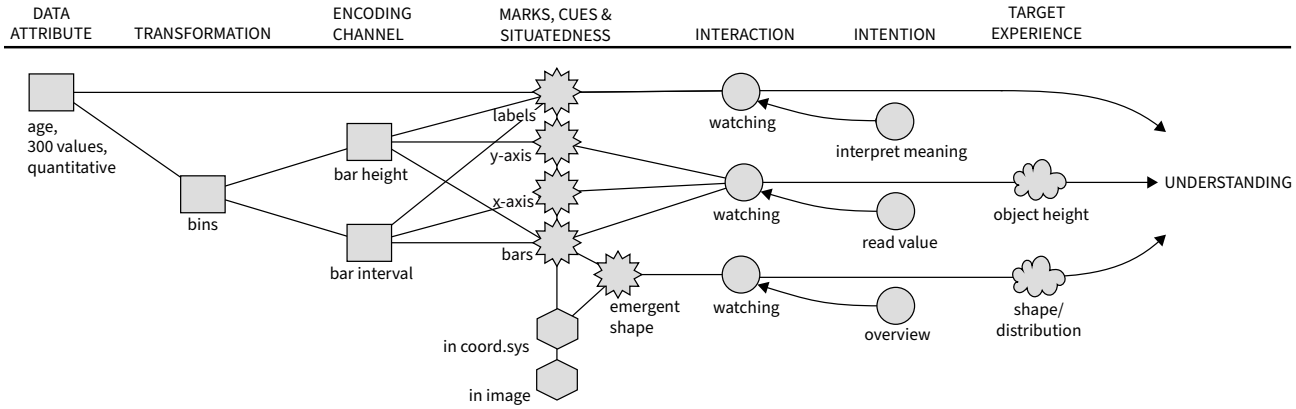

Figure 8: Example of the encoding and decoding that defines a histogram. We can define the idiom as requiring labels, but not a specific type of display device. The observer can intuitively get an instant overview of the emergent shape or intentionally read specific bar values from the same image.

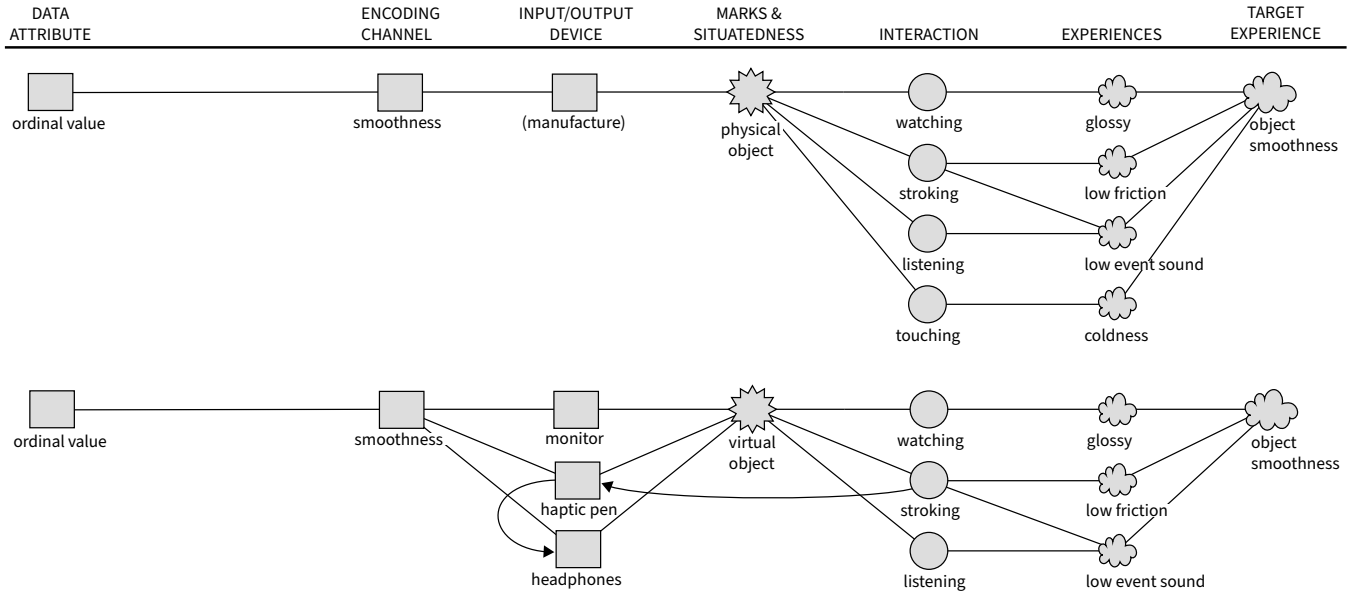

Figure 9: A comparison of how the multisensory experience of an object's smoothness can be encoded for a physical object and a virtual object. Both cases have an encoding channel named smoothness with a matching target experience. They are, however, not the same encoding channel and contain different instructions on how the external artefact is created and responds to interaction.

model, we can represent the idiom as illustrated in Figure 8. In the use case of perceptualisation, we must always provide a means for translating the meaning [29]. For instance, a legend is provided alongside a colour map, and a coordinate axis is often added alongside position encodings. These guiding cues are intuitive to see as part of the encoding channel, which might further have a major impact on the precision and may also be further specified in terms of situatedness [4]. Note that the specific display has been excluded from this example, assuming either a paper or a screen of a decent size is used to display the image. What is included is only the strictly required elements for the histogram idiom.

4.4.2 Expressing Rich Multisensory Experiences. For the multisensory experience of smoothness, multiple perceptual abilities and physical properties are combined by considering appearance, feel and sound from interaction, leading to a single yet rich experience [46, 82]. The object property can be used as a channel in data physicalisation, but also for a virtual object that is explorable through extended reality (XR). Simulating interaction with a smooth virtual object would require orchestrating encodings for multiple types of output devices. In Figure 9, we compare two different ways of encoding smoothness. Using the conceptual model, we can see the many things the channels have in common, even when two

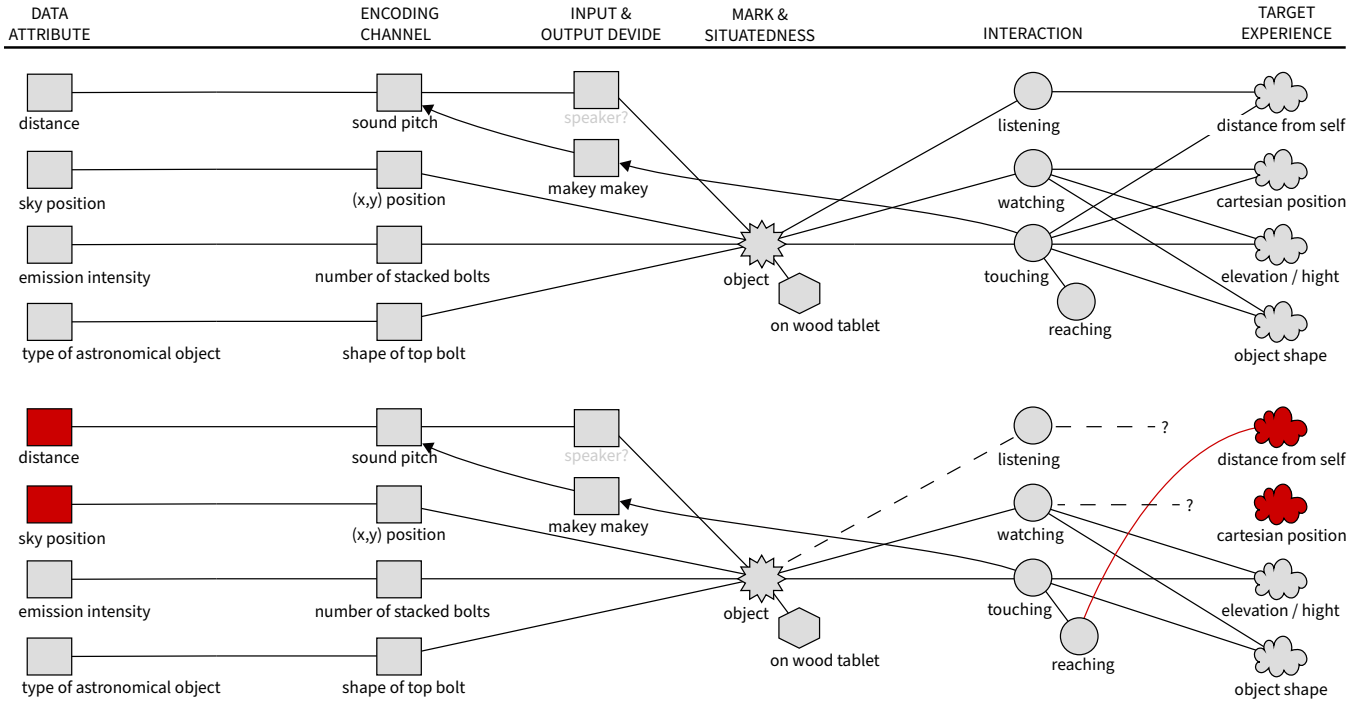

Figure 10: In this example, which is based on a 2.5D map encoding of data on radio-wave emissions from different objects in space [97], evaluations revealed that an able-visioned participant confused the arm movement required to reach a small object as encoding the distance rather than the sky position.

completely different encoding channels and types of display devices are used. For a physical object, the display device is a physical object manufactured according to instructions provided via the encoding channel.

4.4.3 Overview and Analysis of Solutions. A potential use case for the conceptual model is its ability to visualise the overall encoding and decoding process, making it easier to present the setup of used display devices and to analyse why the design was successful or not. In Figure 10, we show an example by Varano and Zanella [97] comparing two different interpretations of the multimodal interface for astronomical data illustrated in Figure 11. By touching an object on the board, users hear a sound pitch representing the distance to the astronomical body mapped to that object. Evaluations of the interface, conducted with both sighted and blind users, revealed that most participants successfully interpreted the mapping. However, one sighted participant confused the distance to the astronomical object with its Cartesian position as they reached to touch it. Both the position relative to a person and the real-world meaning of the data attribute can be naturally linked to the distance relative to a user, potentially causing the confusion shown in red in the lower mapping.

A different designer who is considering using small objects, buttons or dots on a touch map could be interested in finding the publication related to this project in the future. Storing the conceptual model as a graph with various node types in a database opens possibilities for locating similar projects and grants access to context-related design theory. Creating links between different design solutions depends on reusing the same concept, making it reliant on more abstract classifications of marks, situatedness, interaction and target experiences. A detail that is not obvious in the image, but can be defined further in the sound pitch encoding channel, is how the touch event triggers the sound. The code snippet used for encoding and the mapping overview from the conceptual model complement each other in expressing the design solution for humans and, potentially, algorithms in the future.

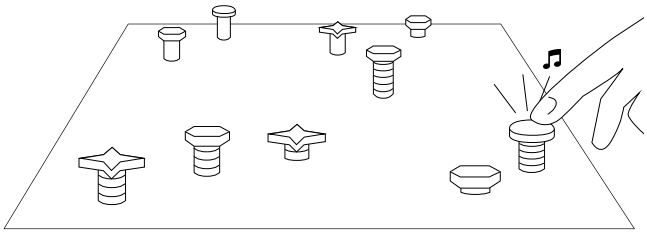

Figure 11: Illustration of a multimodal interface by Varano and Zanella [97] using a physical board with objects that trigger a sound when touched.

4.4.4 Final Comments. The conceptual model has been developed through multiple iterations, during which insights for improvement were gained by testing it against existing mapping examples and by comparing it with aspects mentioned in the literature that are valuable for clarification at the channel level. Today, the primary

value of the model lies in its ability to present details of a perceptualisation artefact developed for real use cases or experimental studies. It can help provide details that are otherwise easily overlooked in documentation and make details easier for readers to understand alongside explanations in the text.

In the future, it could support the unification of theory and structural information within a larger knowledge base. Without standardised terminology and a well-selected set of classifications, choosing the type of channel, situatedness or intention might be unintuitive and lead to synonyms and cluttered data. Both the model and concept definitions must be further validated and refined with a larger number of examples to ensure they can be used consistently across many different fields. The model's current uses do not impose as strong requirements on researchers and designers to use it consistently, but allow the model to be adapted to best present the relevant details of each case. To include all details available through the model in a graph database, it is likely best to derive parts directly from a prototyping tool. This would both make it easier to systematically gather all technical details needed for easy reuse of solutions and avoid manual labour for parts already known to the system. A human can complement the information with other details, such as situatedness, interaction and interpretation. Each of these factors helps build large networks that can be analysed for patterns of what makes a good solution in different contexts and provides access to closely related design theory.

5 Future Work and Conclusion

The present work offers an initial step in an effort that will require years of sustained contributions from multiple research disciplines, yet promises substantial benefits. A shared database could become a particularly valuable resource for managing context-specific knowledge across data perceptualisation disciplines. However, its effectiveness depends on a shared vocabulary and agreed-upon concepts. Unifying the theory alone is insufficient. It is equally necessary to support practices that enable the evolution of the content and the resources used to manage and deliver it to both human users and software systems, as discussed earlier in Section 3.

The refinement of such a theory—and of the schema used to organise it—must therefore proceed incrementally, with continuous input from the relevant subfields. The coexistence of abstract and explicit concepts is characteristic not only of design theories, but also of efforts to manage generalisable findings in perception, health, education and complex natural systems. This makes it pertinent to examine solutions developed in domains beyond data physicalisation.

Computer scientists, interface designers and experts in collective intelligence have an initial, central role in developing systems where an evolving theory resource is made available in practice, while the fields with relevant knowledge to inform the design of data perceptualisation must help in further defining what knowledge is essential and provide it in forms that are accessible and actionable for those without equivalent expertise. We therefore welcome cross-disciplinary research collaborations addressing this substantial challenge, and strongly believe that in the future, DPDT can deliver value through a shared knowledge database that is structured, usable and refined through collective effort.

In this paper, we examined the opportunities and challenges of establishing a unifying and accessible design theory for data perceptualisation. By analysing theory and practice across closely related subfields, we identified structural inconsistencies that hinder interdisciplinary comparison and reuse of knowledge. In response, we introduced a data perceptualisation design theory (DPDT) as a design-theoretical perspective and proposed a set of complementary contributions to improve conceptual clarity and accessibility.

We refined the notion of channels by explicitly distinguishing between encoding channels, understood as concrete design instructions, and full perceptual channels that span data, physical manifestation, interaction and experience. This distinction helps reconcile differences in terminology and scope across subfields while remaining compatible with existing practices. We further presented a perceptualisation pipeline and a conceptual model that together support the description, documentation, comparison and constructive discussion of perceptualisation artefacts across interdependent research communities.

Beyond conceptual unification, we argued that effective theory must be supported by practices and resources that facilitate evolution, reuse and application. In particular, structured and shared representations of design knowledge are necessary to address the current fragmentation of the literature, the limited comparability of studies and barriers to interdisciplinary access. While the presented work does not yet provide such infrastructure, it outlines requirements and design directions that can inform future systems.

This paper does not propose a complete or finished theory. It rather establishes a common vocabulary, conceptual grounding and a set of models intended to support discussion, comparison and incremental refinement across the various data perceptualisation research subfields. We see our data perceptualisation design theory as a starting point for continued cross-disciplinary collaboration and for developing resources that better support the design, accessibility and study of interfaces with multisensory data mappings.

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References

[1] Janet Anderson. 2005. Creating an Empirical Framework for Sonification Design. In *Proceedings of ICAD 2005, International Conference on Auditory Display*. Limerick, Ireland. https://www.icad.org/Proceedings/2005/Anderson2005.pdf

[2] S. Sandra Bae, Clement Zheng, Mary Etta West, Ellen Yi-Luen Do, Samuel Huron, and Danielle Albers Szafir. 2022. Making Data Tangible: A Cross-disciplinary Design Space for Data Physicalization. In *Proceedings of CHI 2022, SIGCHI Conference on Human Factors in Computing Systems*. New Orleans, USA. https://doi.org/10.1145/3491102.3501939

[3] Jacques Bertin. 1967. *Sémiologie graphique: les diagrammes, les réseaux, les cartes*. Gauthier-Villars.

[4] Anastasia Bezerianos and Petra Isenberg. 2012. Perception of Visual Variables on Tiled Wall-sized Displays for Information Visualization Applications. *IEEE Transactions on Visualization and Computer Graphics* 18, 12 (October 2012). https://doi.org/10.1109/TVCG.2012.251

[5] Ayush Bhardwaj and Jin Ryong Kim. 2024. Tangible Data: Immersive Data Exploration with Touch. In *Proceedings of SIGGRAPH 2024, Special Interest Group on Computer Graphics and Interactive Techniques Conference*. Denver, USA. https://doi.org/10.1145/3641517.3664398

[6] Alethea L. Blackler and Jörn Hurtienne. 2007. Towards a Unified View of Intuitive Interaction: Definitions, Models and Tools Across the World. *MMI-Interaktiv* 13 (August 2007). https://www.mmi-interaktiv.de/uploads/media/04-Blackler_Hurtienne_02.pdf

[7] Terri L. Bonebright and John H. Flowers. 2011. Evaluation of Auditory Display. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G. Neuhoff (Eds.). Logos Verlag. https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf

[8] Nathalie Bressa, Henrik Korsgaard, Aurélien Tabard, Steven Houben, and Jo Vermeulen. 2022. What's the Situation with Situated Visualization? A Survey and Perspectives on Situatedness. *IEEE Transactions on Visualization and Computer Graphics* 28, 1 (January 2022). https://doi.org/10.1109/TVCG.2021.3114835

[9] Lorna M. Brown, Stephen A. Brewster, and Helen C. Purchase. 2005. A First Investigation Into the Effectiveness of Tactons. In *Proceedings of WHC 2005, Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. Pisa, Italy. https://doi.org/10.1109/WHC.2005.6

[10] Lorna M. Brown, Stephen A. Brewster, Ramesh Ramloll, Mike Burton, and Beate Riedel. 2003. Design Guidelines for Audio Presentation of Graphs and Tables. In *Proceedings of ICAD 2003, International Conference on Auditory Display*. Boston, USA. https://eprints.gla.ac.uk/3196/1/Brown_Guidelines_final.pdf

[11] Stuart K. Card, Jock Mackinlay, and Ben Shneiderman. 1999. *Readings in Information Visualization: Using Vision to Think*. Morgan Kaufmann.

[12] Simon Carlile. 2011. Psychoacoustics. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G. Neuhoff (Eds.). Logos Verlag. https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf

[13] Dempsey H. Chang. 2007. *A Gestalt-Taxonomy for Designing Multimodal Information Displays*. Ph. D. Dissertation. University of Canberra. https://doi.org/10.26191/544p-na94

[14] William S. Cleveland and Robert McGill. 1984. Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. *J. Amer. Statist. Assoc.* 79, 387 (September 1984). https://doi.org/10.1080/01621459.1984.10478080

[15] Nigel Cross. 2001. Design/Science/Research: Developing a Discipline. In *Proceedings of the Asian Design Conference: International Symposium of Design Science*. Seoul, Korea.

[16] Alberto de Campo. 2007. Toward a Data Sonification Design Space Map. In *Proceedings of ICAD 2007, International Conference on Auditory Display*. Montreal, Canada. https://icad.org/Proceedings/2007/deCampo2007.pdf

[17] Auriol Degbelo. 2022. FAIR Geovisualizations: Definitions, Challenges, and the Road Ahead. *International Journal of Geographical Information Science* 36, 6 (2022). https://doi.org/10.1080/13658816.2021.1983579

[18] Pierre Dragicevic and Yvonne Jansen. 2026. List of Physical Visualizations. www.dataphys.org/list.

[19] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. 2021. Data Physicalization. In *Handbook of Human Computer Interaction*, Jean Vanderdonckt, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing. https://doi.org/10.1007/978-3-319-27648-9_94-1

[20] Xiaojiao Du, Kadek Ananta Satriadi, Adam Drogemuller, Brandon J. Matthews, Ross Smith, James A. Walsh, and Andrew Cunningham. 2024. That's Rough! Encoding Data into Roughness for Physicalization. In *Proceedings of CHI 2024, SIGCHI Conference on Human Factors in Computing Systems*. Honolulu, USA. https://doi.org/10.1145/3613904.3641900

[21] Gaël Dubus and Roberto Bresin. 2013. A Systematic Review of Mapping Strategies for the Sonification of Physical Quantities. *PLOS ONE* 8, 12 (December 2013). https://doi.org/10.1371/journal.pone.0082491

[22] David J. Duke, Philip J. Barnard, David A. Duce, and Jon May. 1998. Syndetic Modelling. *Human-Computer Interaction* 13, 4 (December 1998). https://doi.org/10.1207/s15327051hci1304_1

[23] Lucy E. Dunne and Barry Smyth. 2007. Psychophysical Elements of Wearability. In *Proceedings of CHI 2007, SIGCHI Conference on Human Factors in Computing Systems*. San Jose, USA. https://doi.org/10.1145/1240624.1240674

[24] Madison Elliott, Christine Nothelfer, Cindy Xiong, and Danielle Szafir. 2021. A Design Space of Vision Science Methods for Visualization Research. *IEEE Transactions on Visualization and Computer Graphics* 27, 2 (February 2021). https://doi.org/10.1109/TVCG.2020.3029413

[25] Kajetan Enge, Elias Elmquist, Valentina Caiola, Niklas Rönnberg, Alexander Rind, Michael Iber, Sara Lenzi, Fangfei Lan, Robert Höldrich, and Wolfgang Aigner. 2024. Open Your Ears and Take a Look: A State-of-the-Art Report on the Integration of Sonification and Visualization. *Computer Graphics Forum* 43, 3 (June 2024). https://doi.org/10.1111/cgf.15114

[26] Kajetan Enge, Alexander Rind, Michael Iber, Robert Höldrich, and Wolfgang Aigner. 2022. Towards Multimodal Exploratory Data Analysis: SoniScope as a Prototypical Implementation. In *Proceedings of EuroVis 2022, Eurographics Conference on Visualization*. Rome, Italy. https://doi.org/10.2312/evs.20221095

[27] Matthew T. Flavin, Kyoung-Ho Ha, Zengrong Guo, Shupeng Li, Jin-Tae Kim, Tara Saxena, Dimitrios Simatos, Fatimah Al-Najjar, Yuxuan Mao, Shishir Bandapalli, et al. 2024. Bioelastic State Recovery for Haptic Sensory Substitution. *Nature* 635 (November 2024). https://doi.org/10.1038/s41586-024-08155-9

[28] John H. Flowers. 2005. Thirteen Years of Reflection on Auditory Graphing: Promises, Pitfalls and Potential New Directions. In *Proceedings of ICAD 2005, International Conference on Auditory Display*. Limerick, Ireland. https://www.icad.org/Proceedings/2005/Flowers2005.pdf

[29] Amy Rae Fox and James D. Hollan. 2023. Visualization Psychology: Foundations for an Interdisciplinary Research Program. In *Visualization Psychology*. Springer. https://doi.org/10.1007/978-3-031-34738-2_9

[30] Shirley Gregor and David Jones. 2007. The Anatomy of a Design Theory. *Journal of the Association for Information Systems* 8, 5 (May 2007). https://doi.org/10.17705/1jais.00129

[31] Amy L. Griffin. 2001. Feeling It Out: The Use of Haptic Visualization for Exploratory Geographic Analysis. *Cartographic Perspectives* 39 (June 2001). https://doi.org/10.14714/CP39.636

[32] Georges G. Grinstein and Stuart Smith. 1990. Perceptualization of Scientific Data. In *Extracting Meaning from Complex Data: Processing, Display, Interaction*. https://doi.org/10.1117/12.19986

[33] Florian Grond and J. Berger. 2011. Parameter Mapping Sonification. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G. Neuhoff (Eds.). Logos Verlag. https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf

[34] Katharina Groß-Vogt, Kajetan Enge, and IOhannes M. Zmölnig. 2023. Reflecting on Qualitative and Quantitative Data to Frame Criteria for Effective Sonification Design. In *Proceedings of AM 2023, International Audio Mostly Conference*. Edinburgh, United Kingdom. https://doi.org/10.1145/3616195.3616233

[35] Thomas Hermann, Andy Hunt, and John G. Neuhoff. 2011. Introduction. In *The Sonification Handbook*, Thomas Hermann, Andy Hunt, and John G. Neuhoff (Eds.). Logos Verlag. https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf

[36] Aidan Hogan, Eva Blomqvist, Michael Cochez, Claudia D'amato, Gerard De Melo, Claudio Gutierrez, Sabrina Kirrane, José Emilio Labra Gayo, Roberto Navigli, Sebastian Neumaier, Axel-Cyrille Ngonga Ngomo, Axel Polleres, Sabbir M. Rashid, Anisa Rula, Lukas Schmelzeisen, Juan Sequeda, Steffen Staab, and Antoine Zimmermann. 2021. Knowledge Graphs. *Comput. Surveys* 54, 4 (July 2021). https://doi.org/10.1145/3447772

[37] Trevor Hogan. 2018. Data Sensification: Beyond Representation Modality, Toward Encoding Data in Experience. In *Proceedings of DRS 2018, DRS International Conference*. Limerick, Ireland. https://doi.org/10.21606/drs.2018.238

[38] Trevor Hogan and Eva Hornecker. 2017. Towards a Design Space for Multisensory Data Representation. *Interacting with Computers* 29, 2 (March 2017). https://doi.org/10.1093/iwc/iww015

[39] James Hollan, Edwin Hutchins, and David Kirsh. 2000. Distributed Cognition: Toward a New Foundation for Human-Computer Interaction Research. *ACM Transactions on Computer-Human Interaction* 7, 2 (June 2000). https://doi.org/10.1145/353485.353487

[40] Lars Erik Holmquist. 2023. Bits are Cheap, Atoms are Expensive: Critiquing the Turn Towards Tangibility in HCI. In *Extended Abstracts of CHI 2023, SIGCHI Conference on Human Factors in Computing Systems*. Hamburg, Germany. https://doi.org/10.1145/3544549.3582744

[41] Eva Hornecker, Trevor Hogan, Uta Hinrichs, and Rosa Van Koningsbruggen. 2023. A Design Vocabulary for Data Physicalization. *ACM Transactions on Computer-Human Interaction* 1, 2 (August 2023). https://doi.org/10.1145/3617366

[42] Kevin Hu, Michiel A. Bakker, Stephen Li, Tim Kraska, and César Hidalgo. 2019. VizML: A Machine Learning Approach to Visualization Recommendation. In *Proceedings of CHI 2019, SIGCHI Conference on Human Factors in Computing Systems*. Glasgow, United Kingdom. https://doi.org/10.1145/3290605.3300358

[43] Weiming Huang and Lars Harrie. 2020. Towards Knowledge-based Geovisualisation Using Semantic Web Technologies: A Knowledge Representation Approach Coupling Ontologies and Rules. *International Journal of Digital Earth* 13, 9 (2020). https://doi.org/10.1080/17538947.2019.1604835

[44] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials. *Interactions* 19, 1 (January 2012). https://doi.org/10.1145/2065327.2065337

[45] Yvonne Jansen and Pierre Dragicevic. 2013. An Interaction Model for Visualizations Beyond the Desktop. *IEEE Transactions on Visualization and Computer Graphics* 19, 12 (December 2013). https://doi.org/10.1109/TVCG.2013.134

[46] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of CHI 2015, SIGCHI Conference on Human Factors in Computing Systems*. Seoul Republic of Korea. https://doi.org/10.1145/2702123.2702180

[47] Yvonne Jansen and Kasper Hornbæk. 2016. A Psychophysical Investigation of Size as a Physical Variable. *IEEE Transactions on Visualization and Computer Graphics* 22, 1 (January 2016). https://doi.org/10.1109/TVCG.2015.2467951

[48] Qi Jiang, Guodao Sun, Tong Li, Jingwei Tang, Wang Xia, Sujia Zhu, and Ronghua Liang. 2024. Qutaber: Task-based Exploratory Data Analysis with Enriched Context Awareness. 27, 3 (March 2024). https://doi.org/10.1007/s12650-024-00975-1

[49] Takuya Jodai, Masahiko Terao, Lynette A. Jones, and Hsin-Ni Ho. 2023. Determination of the Thermal-tactile Simultaneity Window for Multisensory Cutaneous Displays*. In *Proceedings of WHC 2023, World Haptics Conference*. Delft, The

Netherlands. https://doi.org/10.1109/WHC56415.2023.10224482
[50] Lynette A. Jones and Hong Z. Tan. 2013. Application of Psychophysical Techniques to Haptic Research. *IEEE Transactions on Haptics* 6, 3 (July 2013). https://doi.org/10.1109/TOH.2012.74
[51] Max Kleiman-Weiner and Jonathan Berger. 2006. The Sound of One Arm Swinging: A Model for Multidimensional Auditory Display of Physical Motion. In *Proceedings of ICAD 2006, International Conference on Auditory Display*. London, United Kingdom.
[52] Robert Kosara. 2016. An Empire Built On Sand: Reexamining What We Think We Know About Visualization. In *Proceedings of BELIV 2016, Workshop on Beyond Time and Errors on Novel Evaluation Methods for Visualization*. Baltimore, USA. https://doi.org/10.1145/2993901.2993909
[53] Robert Kosara. 2019. Evidence for Area as the Primary Visual Cue in Pie Charts. In *Proceedings of VIS 2019, IEEE Visualization Conference*. Vancouver, Canada. https://doi.org/10.1109/VISUAL.2019.8933547
[54] Robert Kosara and Steve Haroz. 2018. Skipping the Replication Crisis in Visualization: Threats to Study Validity and How to Address Them: Position Paper. In *Proceedings of BELIV 2018, IEEE Conference on Evaluation and Beyond - Methodological Approaches for Visualization*. Berlin, Germany. https://doi.org/10.1109/BELIV.2018.8634392
[55] Mohammad Amin Kuhail, Jose Berengueres, Fatma Taher, and Mariam Al Kuwaiti. 2024. Challenges of Designing Haptic Experiences. In *Advances, Applications and the Future of Haptic Technology*. Springer. https://doi.org/10.1007/978-3-031-70588-5_4
[56] Pascal Le Masson, Armand Hatchuel, and Benoit Weil. 2020. C-K Design Theory. In *Integrated Design Engineering: Interdisciplinary and Holistic Product Development*. Springer. https://minesparis-psl.hal.science/hal-03042533v1
[57] Sara Lenzi. 2021. *The Design of Data Sonification. Design Processes, Protocols and Tools Grounded in Anomaly Detection.* PhD thesis. Politecnico di Milano, Milano, Italy. https://hdl.handle.net/10589/177079
[58] PerMagnus Lindborg, Shauhrat S. Chopra, and Katharina Groß-Vogt. 2023. Editorial: Data Perceptualization for Climate Science Communication. *Frontiers in Psychology* 14 (August 2023). https://doi.org/10.3389/fpsyg.2023.1263971
[59] Karon MacLean and Mario Enriquez. 2003. Perceptual Design of Haptic Icons. In *Proceedings of EuroHaptics 2003, International Conference on Haptics: Perception, Devices and Scenarios*. Dublin, Ireland. https://www.cs.ubc.ca/~murphy/cpsc590/EH03-hapticIcon-reprint.pdf
[60] Caitlyn M. McColeman. 2017. *Exploring Human Cognition Through Multivariate Data Visualization.* Ph. D. Dissertation. Simon Fraser University, Burnaby, Canada.
[61] Jon McCormack, Jonathan C. Roberts, Benjamin Bach, Carla Dal Sasso Freitas, Takayuki Itoh, Christophe Hurter, and Kim Marriott. 2018. Multisensory Immersive Analytics. In *Immersive Analytics*. Springer. https://doi.org/10.1007/978-3-030-01388-2_3
[62] Thomas Muender, Michael Bonfert, Anke Verena Reinschluessel, Rainer Malaka, and Tanja Döring. 2022. Haptic Fidelity Framework: Defining the Factors of Realistic Haptic Feedback for Virtual Reality. In *Proceedings of CHI 2022, SIGCHI Conference on Human Factors in Computing Systems*. New Orleans, USA. https://doi.org/10.1145/3491102.3501953
[63] Tamara Munzner. 2014. *Visualization Analysis and Design.* A K Peters/CRC Press. https://doi.org/10.1201/b17511
[64] Michael A. Nees. 2019. Eight Components of a Design Theory of Sonification. In *Proceedings of ICAD 2019, International Conference on Auditory Display*. Newcastle-upon-Tyne, United Kingdom. https://doi.org/10.21785/icad2019.048
[65] Keith V. Nesbitt. 2001. Modeling the Multi-sensory Design Space. In *Proceedings of APVis 2001, Asia-Pacific Symposium on Information Visualisation*. Sydney, Australia. https://doi.org/10.5555/564040.564044
[66] Keith V. Nesbitt. 2006. Modelling Human Perception to Leverage the Reuse of Concepts Across the Multi-sensory Design Space. In *Proceedings of APCCM 2006, Asia-Pacific Conference on Conceptual Modelling*. Hobart, Australia. https://dl.acm.org/citation.cfm?id=1151863
[67] John G. Neuhoff. 2019. Is Sonification Doomed to Fail?. In *Proceedings of ICAD 2019, International Conference on Auditory Display*. Newcastle-upon-Tyne, United Kingdom. https://doi.org/10.21785/icad2019.069
[68] John G. Neuhoff, Rebecca Knight, and Joseph Wayand. 2002. Pitch Change, Sonification, and Musical Expertise: Which Way is Up?. In *Proceedings of ICAD 2002, International Conference on Auditory Display*. Kyoto, Japan. https://icad.org/Proceedings/2002/NeuhoffKnight2002.pdf
[69] Tommy Nguyen. 2026. *Bridging a Disciplinary Archipelago: A Trust-centered Community Center for Haptic Design.* Master's thesis. University of British Columbia, Vancouver, Canada.
[70] Marianna Obrist, Sue Ann Seah, and Sriram Subramanian. 2013. Talking About Tactile Experiences. In *Proceedings of CHI 2013, SIGCHI Conference on Human Factors in Computing Systems*. Paris France. https://doi.org/10.1145/2470654.2466220
[71] Sharon Oviatt and Philip R. Cohen. 2015. *The Paradigm Shift to Multimodality in Contemporary Computer Interfaces.* Morgan & Claypool Publishers.
[72] Paul Parsons. 2023. Preparing Future Data Visualization Designers for Professional Practice. In *Proceedings of EduVis, IEEE VIS Workshop on Visualization Education, Literacy, and Activities*. Melbourne, Australia. https://doi.org/10.1109/EduVis60792.2023.00010
[73] Biswaksen Patnaik, Andrea Batch, and Niklas Elmqvist. 2019. Information Olfactation: Harnessing Scent to Convey Data. *IEEE Transactions on Visualization and Computer Graphics* 25, 1 (2019). https://doi.org/10.1109/TVCG.2018.2865237
[74] Tristan Peng, Hongchan Choi, and Jonathan Berger. 2023. Siren: Creative and Extensible Sonification on the Web. In *Proceedings of ICAD 2023, International Conference on Auditory Display*. Linköping University, Sweden. https://doi.org/10.21785/icad2023.6167
[75] Luca Podo, Bardh Prenkaj, and Paola Velardi. 2025. Agnostic Visual Recommendation Systems: Open Challenges and Future Directions. *IEEE Transactions on Visualization and Computer Graphics* 31, 3 (2025). https://doi.org/10.1109/TVCG.2024.3374571
[76] Luca Podo and Paola Velardi. 2022. Plotly.plus, an Improved Dataset for Visualization Recommendation. In *Proceedings of CIKM 2022, International Conference on Information & Knowledge Management*. Atlanta, USA. https://doi.org/10.1145/3511808.3557669
[77] Helen C. Purchase, Natalia Andrienko, Thomas J. Jankun-Kelly, and Matthew Ward. 2008. Theoretical Foundations of Information Visualization. In *Information Visualization: Human-centered Issues and Perspectives*, Andreas Kerren, John T. Stasko, Jean-Daniel Fekete, and Chris North (Eds.). Springer. https://doi.org/10.1007/978-3-540-70956-5_3
[78] Ghulam Jilani Quadri and Paul Rosen. 2022. A Survey of Perception-based Visualization Studies by Task. *IEEE Transactions on Visualization and Computer Graphics* 28, 12 (December 2022). https://doi.org/10.1109/TVCG.2021.3098240
[79] Michael Quinton, Iain McGregor, and David Benyon. 2018. Investigating Effective Methods of Designing Sonifications. In *Proceedings of ICAD 2018, International Conference on Auditory Display*. Houghton, USA. https://doi.org/10.21785/icad2018.011
[80] Champika Ranasinghe and Auriol Degbelo. 2023. Encoding Variables, Evaluation Criteria and Evaluation Methods for Data Physicalizations: A Review. *Multimodal Technologies and Interaction* 7, 7 (2023). https://doi.org/10.3390/mti7070073
[81] Dennis Reinsch and Thomas Hermann. 2023. Sonecules: A Python Sonification Architecture. In *Proceedings of ICAD 2023, International Conference on Auditory Display*. Norrköping, Sweden. https://doi.org/10.21785/icad2023.5580
[82] Stephen Roddy and Brian Bridges. 2016. Sounding Human with Data: The Role of Embodied Conceptual Metaphors and Aesthetics in Representing and Exploring Data Sets. In *Proceedings of MusTWork 2016, Music Technology Workshop*. Dublin, Ireland.
[83] Robert E. Roth. 2017. Visual Variables. In *International Encyclopedia of Geography*. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118786352.wbieg0761
[84] Niklas Rönnberg and Camilla Forsell. 2022. Questionnaires Assessing Usability of Audio-Visual Representations. In *Proceedings of the AVI 2022 Workshop on Audio-Visual Analytics*. Rome, Italy.
[85] Kim Sauvé and Steven Houben. 2022. From Data to Physical Artifact: Challenges and Opportunities in Designing Physical Data Artifacts for Everyday Life. *Interactions* 29, 2 (2022). https://doi.org/10.1145/3511670
[86] Oliver Schneider, Karon MacLean, Colin Swindells, and Kellogg Booth. 2017. Haptic Experience Design: What Hapticians Do and Where They Need Help. *International Journal of Human-Computer Studies* 107 (November 2017). https://doi.org/10.1016/j.ijhcs.2017.04.004
[87] Kamran Sedig and Paul Parsons. 2022. *Design of Visualizations for Human-Information Interaction: A Pattern-based Framework*. Springer Nature.
[88] Beat Signer, Payam Ebrahimi, Timothy J. Curtin, and Ahmed K.A. Abdullah. 2018. Towards a Framework for Dynamic Data Physicalisation. In *International Workshop Toward a Design Language for Data Physicalization*. Berlin, Germany. https://researchportal.vub.be/files/75811068/towards_a_framework_for_dynamic_data_physicalisation.pdf
[89] Hong Jun Song and Kirsty Beilharz. 2008. Aesthetic and Auditory Enhancements for Multi-Stream Information Sonification. In *Proceedings of DIMEA 2008, International Conference on Digital Interactive Media in Entertainment and Arts*. Athens, Greece. https://doi.org/10.1145/1413634.1413678
[90] Rafael D. Sorkin. 1987. Design of Auditory and Tactile Displays. In *Handbook of Human Factors*, Gavriel Salvendy (Ed.). McGraw-Hill, New York.
[91] Laura South, David Saffo, Olga Vitek, Cody Dunne, and Michelle A. Borkin. 2022. Effective Use of Likert Scales in Visualization Evaluations: A Systematic Review. *Computer Graphics Forum* 41, 3 (2022). https://doi.org/10.1111/cgf.14521
[92] Lothar Spillmann, Li-Chuan Hsu, Wei Wang, Chien-Chung Chen, Chun-I Yeh, and Chia-Huei Tseng. 2023. Gestalt Neurons and Emergent Properties in Visual Perception: A Novel Concept for the Transformation From Local to Global Processing. *Journal of Vision* 23, 14 (December 2023). https://doi.org/10.1167/jov.23.14.4
[93] Simon Stusak. 2015. Exploring the Potential of Physical Visualizations. In *Proceedings of TEI 2015, International Conference on Tangible, Embedded, and Embodied Interaction*. Stanford, USA. https://doi.org/10.1145/2677199.2691604

[94] Simon Stusak, Andreas Butz, and Aurélien Tabard. 2018. Variables for Data Physicalization Units. In *Workshop Toward a Design Language for Data Physicalization*. Berlin, Germany.

[95] Alistair Sutcliffe. 2000. On the Effective Use and Reuse of HCI Knowledge. *ACM Transactions on Computer-Human Interaction* 7, 2 (2000). https://doi.org/10.1145/353485.353488

[96] Hui Tang and D.J. Beebe. 2006. An Oral Tactile Interface for Blind Navigation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 14, 1 (March 2006). https://doi.org/10.1109/TNSRE.2005.862696

[97] Stefania Varano and Anita Zanella. 2023. Design and Evaluation of a Multisensory Representation of Scientific Data. *Frontiers in Education* 8 (2023). https://doi.org/10.3389/feduc.2023.1082249

[98] Bruce N. Walker. 2007. Consistency of Magnitude Estimations with Conceptual Data Dimensions Used For Sonification. *Applied Cognitive Psychology* 21, 5 (2007). https://doi.org/10.1002/acp.1291

[99] Shu Wang, Peiyuan Qiu, Yunqiang Zhu, Jie Yang, Peng Peng, Yan Bai, Gengze Li, Xiaoliang Dai, and Yanmin Qi. 2025. Review, Framework, and Future Perspectives of Geographic Knowledge Graph (GeoKG) Quality Assessment. 28, 4 (2025). https://doi.org/10.1080/10095020.2024.2403785

[100] Christopher D. Wickens, Justin G. Hollands, Simon Banbury, and Raja Parasuraman. 2013. *Engineering Psychology and Human Performance* (4 ed.). Pearson.

[101] Hadley Wickham. 2010. A Layered Grammar of Graphics. *Journal of Computational and Graphical Statistics* 19, 1 (January 2010). https://doi.org/10.1198/jcgs.2009.07098

[102] Lisa D. Wijsen, Denny Borsboom, and Anna Alexandrova. 2022. Values in Psychometrics. *Perspectives on Psychological Science* 17, 3 (May 2022). https://doi.org/10.1177/17456916211014183

[103] Leland Wilkinson and Graham Wills. 2005. *The Grammar of Graphics* (2 ed.). Springer. https://doi.org/10.1007/0-387-28695-0

[104] Junran Yang, Péter Ferenc Gyarmati, Zehua Zeng, and Dominik Moritz. 2023. Draco 2: An Extensible Platform to Model Visualization Design. In *Proceedings of VIS 2023, International Conference on Visualization and Visual Analytics*. Melbourne, Australia. https://doi.org/10.1109/VIS54172.2023.00042

[105] Zehua Zeng and Leilani Battle. 2023. A Review and Collation of Graphical Perception Knowledge for Visualization Recommendation. In *Proceedings of CHI 2023, SIGCHI Conference on Human Factors in Computing Systems*. Hamburg, Germany. https://doi.org/10.1145/3544548.3581349

[106] Zehua Zeng, Phoebe Moh, Fan Du, Jane Hoffswell, Tak Yeon Lee, Sana Malik, Eunyee Koh, and Leilani Battle. 2022. An Evaluation-focused Framework for Visualization Recommendation Algorithms. *IEEE Transactions on Visualization and Computer Graphics* 28, 1 (2022). https://doi.org/10.1109/TVCG.2021.3114814

[107] Zehua Zeng, Junran Yang, Dominik Moritz, Jeffrey Heer, and Leilani Battle. 2024. Too Many Cooks: Exploring How Graphical Perception Studies Influence Visualization Recommendations in Draco. *IEEE Transactions on Visualization and Computer Graphics* 30, 1 (October 2024). https://doi.org/10.1109/TVCG.2023.3326527

[108] Songheng Zhang, Haotian Li, Huamin Qu, and Yong Wang. 2024. AdaVis: Adaptive and Explainable Visualization Recommendation for Tabular Data. *IEEE Transactions on Visualization and Computer Graphics* 30, 9 (September 2024). https://doi.org/10.1109/TVCG.2023.3316469

[109] Yue Zhao, Yunhai Wang, Xu Luo, Yanyan Wang, and Jean-Daniel Fekete. 2025. Libra: An Interaction Model for Data Visualization. In *Proceedings of CHI 2025, SIGCHI Conference on Human Factors in Computing Systems*. Yokohama, Japan. https://doi.org/10.1145/3706598.3713769

[110] Mounia Ziat. 2023. Haptics for Human-Computer Interaction: From the Skin to the Brain. *Foundations and Trends in Human–Computer Interaction* 17, 1–2 (February 2023). https://doi.org/10.1561/1100000061

[111] Tim Ziemer and Holger Schultheis. 2019. Psychoacoustical Signal Processing for Three-dimensional Sonification. In *Proceedings of ICAD 2019, International Conference on Auditory Display*. Sydney, Australia. https://doi.org/10.21785/icad2019.018

[112] Tim Ziemer and Holger Schultheis. 2022. PAMPAS: A PsychoAcoustical Method for the Perceptual Analysis of Multidimensional Sonification. *Frontiers in Neuroscience* 16 (October 2022). https://doi.org/10.3389/fnins.2022.930944

[113] Mario Štorga, Mogens Andreasen, and Dorian Marjanović. 2010. The Design Ontology: Foundation for the Design Knowledge Exchange and Management. *Journal of Engineering Design* 21 (August 2010). https://doi.org/10.1080/09544820802322557