High Fidelity Visualization: Parameter Mapping as an Analytical Tool for Assessing Structural Correspondence

Carmen Hull* Jagoda Walny†

ABSTRACT

Encoding theory provides principled guidance for mapping data types to visual channels, but it operates at the data level. Whether a representation's structural form corresponds to the structure of the phenomenon it depicts remains a separate question—one the field currently lacks a tool to assess. We name *structural correspondence* as critical theory for visualization design, define *fidelity* as the degree of structural correspondence between a representation's parameters and the structural properties of the phenomenon it depicts, and propose *parameter mapping* — systematic assessment of each parameter of a representation against the structural properties of its phenomenon — as the analytical tool for assessing it. For each parameter, the method asks: what structural property of the phenomenon does it correspond to (fidelity gained)? What structural dimensions are absent or collapsed (fidelity lost)? What relationships does the representation introduce that the phenomenon does not have (false structure)? Applied to six existing representations spanning visualization, sonification, and physicalization, the framework surfaces patterns of structural and arbitrary coupling, deliberate abstraction, and false structure that current methods do not detect.

Index Terms: Design methodology, data visualization, fidelity, structural correspondence, data physicalization.

Index Terms: Human-centered computing [Visualization]: Visualization design and evaluation methods

1 INTRODUCTION

In the early 1990s, Fitch and Kramer designed an auditory display to monitor patients in intensive care. Their system mapped eight physiological variables –heart rate, blood pressure, temperature, and five others—to two streams of sound, allowing clinicians to monitor a patient's condition by listening rather than watching a bank of screens. Four of the mappings worked intuitively, without training needed: heart rate drove heartbeat rhythm; fibrillation modulated the heartbeat signal the way real fibrillation modulates a real heartbeat. In these cases, the sound's behavior matched the heart's behavior. The other four mappings—blood pressure to pitch, temperature to a filter, CO_2 to brightness, pupillary reflex to a tone—had to be memorized. The correspondence, where it exists, is metaphorical rather than behavioral (higher pressure to higher pitch via "more is up") [11]; clinicians could not read these mappings without dedicated training [4].

These four encoding failures were not perceptual in nature; all eight variables were legible in the auditory stream. What separated success from failure was behavioral correspondence; the successful mappings preserved a behavioral relationship between source and target, where the sound parameter behaved the way the physiological parameter behaves. The distinction between structural and arbitrary coupling matters for design, yet the visualization community does not yet have a tool for assessing this quality. We propose structural correspondence as critical theory for visualization design, define fidelity as the degree of structural correspondence between the parameters of a representation and the structural properties of the phenomenon it depicts, and present parameter mapping as the analytical tool for assessing it: a vocabulary for design decisions the field currently leaves implicit.

Encoding theory offers principled guidance for mapping data types to visual channels [1, 2, 12], but its scope is the data level. These principles describe which channel encodes a quantitative variable most accurately in task-based perception evaluations, while bracketing much of the representation's structural form: spatial arrangement, containment relationships, temporal behavior, and tangible characteristics. A bar chart may encode GDP values with perfect perceptual accuracy — and faithfully so, since GDP is a single number. But the metric itself has already collapsed the economy's structural complexity (interconnected, dynamic, systemic) into a discrete, independent, static value, and the framework makes that prior commitment visible.

Viewers' brains perceive and infer conceptual relationships whether they are encoded or not. In an early empirical demonstration, Ziemkiewicz and Kosara showed that viewers infer conceptual relationships from visual structure (proximity reads as relatedness, containment as hierarchy) whether or not those relationships exist in the data [22, 23]. When a representation's form misaligns with the phenomenon, viewers will often read relationships that are not there.

The distinction introduces the difference between fidelity to the data and fidelity to the phenomenon, which are currently typically conflated but require different metrics. Encoding theory ensures that values are legible from the visual form, however, a representation also makes structural claims about the phenomenon the data describes. Consider Scarr's "Iraq's Bloody Toll" [16] (Fig. 1): a bar chart of wartime casualties that drips downward in red. Direction, weight, and color correspond to properties of the phenomenon, and the chart makes a structural claim about loss. Cotgreave's redesign of the same data [3] shows the bars rising upward in neutral blue, encoding the values with equal accuracy but stripping the structural correspondence with what the numbers represent. Both have fidelity to the data; fidelity to the phenomenon depends on the representation's intent, and parameter mapping makes the structural claims of each version explicit. The same conflation surfaces at scale across institutional practice: a recent analysis of 53 organizational style guides spanning journalism, government, corporate, and academic sectors finds pervasive contradiction in widely adopted recommendations [14], a pattern consistent with guidance without a theory of phenomenon-level fidelity to converge on.

We propose fidelity as the missing concept that helps designers align their work with the appropriate structural correspondence, and the analytic tool of parameter mapping as a systematic assessment of each parameter of a representation against the structural properties of its phenomenon. Together these constitute High Fidelity Visualization (HFV), a framework for assessing structural correspondence between a representation and the phenomenon it depicts. For any representation, parameter mapping asks three questions: (1) which parameters of the representation correspond to which structural properties of the phenomenon, (2) what structural dimensions are absent

*Carmen Hull is with Northeastern University. E-mail: c.hull@northeastern.edu.

†Jagoda Walny is an independent researcher. E-mail: jwalny@gmail.com

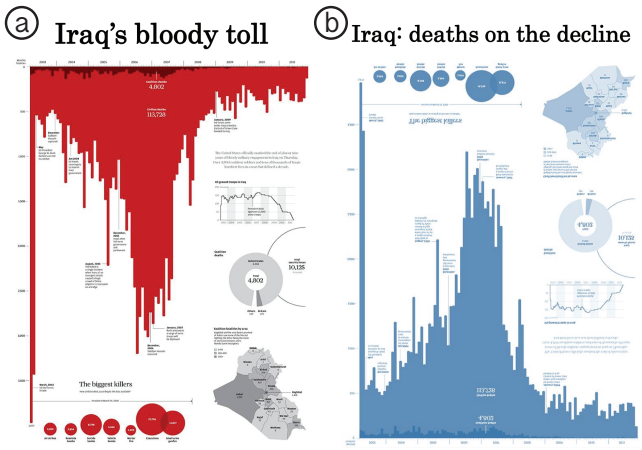

Figure 1: Same data, different fidelity. Scarr's "Iraq's Bloody Toll" [16] (left) and Cotgreave's redesign [3] (right) encode wartime casualties with equal perceptual accuracy, but only the first preserves structural correspondence with what the numbers represent: direction, weight, and color match the phenomenon's properties of loss.

or collapsed, and (3) what structural relationships does the representation introduce that the phenomenon does not have? These prompts produce three columns in an analytical table: fidelity gained, fidelity lost, and false structure. Together, they characterize a representation's structural relationship to its phenomenon.

2 Fidelity as Structural Correspondence

The concept of structural correspondence has deep roots in both cognitive science and semiotics. Visualization theory has approached this property obliquely, through related concepts like data abstraction, visual metaphor, and encoding effectiveness, without naming structural correspondence as a foundational property in its own right. We name it here, and argue that it is critical theory for visualization design. Gentner's structure-mapping theory of analogy establishes that analogical reasoning works through the preservation of relational structure between source and target, with surface similarity playing a much smaller role [5]. Tversky's congruence principle extends this to external representations: a visualization supports cognition when its structural properties are congruent with the conceptual structure of what it depicts [19]. Peirce's account of iconicity provides the semiotic counterpart, distinguishing iconic *images* (signs that work through resemblance) from iconic *diagrams* (signs that work through preserved relational structure) and from iconic *metaphors* (signs that map relational structure across domains) [15]. All three accounts converge on a central claim: representations support reasoning through preserved relational structure. We use fidelity in its structural sense — faithfulness of reproduction, as in audio engineering — rather than as a synonym for perceptual accuracy or veridicality.

Related formulations converge from adjacent fields: Norman's natural mapping identifies structural correspondence between controls and outcomes as the basis for intuitive interaction [13]; Kramer proposed an analogic-symbolic continuum for auditory display that maps onto the structural/arbitrary distinction drawn here [10]; Schloss's work on semantic color association demonstrates that viewers expect color encodings to correspond to the semantic properties of the data they represent [17]. Each describes the property, but none of them yet provide a design tool for assessing it.

Parameter mapping evaluates exactly this kind of correspondence (diagrammatic in Peirce's sense, structural in Gentner's, congruent in Tversky's), at the level of individual parameters. None of these theoretical accounts, however, translates directly into design practice. HFV contributes a method for assessing this correspondence at design time, parameter by parameter, before construction commits the design to a particular set of structural claims.

It is important to note here that fidelity does not require visual resemblance. The classic ball-and-stick model of a molecule looks nothing like quantum-mechanical reality, yet it has been used productively for over a century because its parameters (sphere for atom, rod for bond, angle for bond angle) preserve the relational structure that enables reasoning about reactivity, chirality, and molecular interaction. The parameters that do not map (electron density, orbital shape, quantum behavior) are the ones chemists bracket when reasoning about structure [6]. The model's faithfulness comes from what it omits as much as from what it preserves. Parameter mapping makes this kind of decision visible: it distinguishes *deliberate abstraction* (fidelity collapsed to enable specific reasoning) from *fidelity loss* (structural dimensions absent without analytical purpose).

3 Parameter Mapping as an Analytic Tool

Parameter mapping enters the design process at the casting and winnowing phase [18], when many representational formats are under consideration. To uncover structural correspondence, the designer lists the parameters of each candidate form: spatial arrangement, containment relationships, temporal behavior, material properties, or whatever structural features the form carries that they wish to retain. For each parameter, three questions emerge: Does a corresponding structural property of the phenomenon exist? Does the mapping preserve the behavior of that property, so that when the phenomenon's property changes the representation's parameter changes in a corresponding way? And does the parameter introduce structural relationships the phenomenon does not have? The phenomenon column requires domain expertise the designer may not hold independently, and the framework is designed to structure that collaboration. When responses are tracked across all parameters they produce three categories: fidelity gained (correspondence achieved), fidelity lost (structural dimensions absent), and false structure (relationships imposed). Table 1 demonstrates this tool applied to six existing representations; each row is one parameter assessed against these three questions. When experts reach for source domains to describe a phenomenon, they externalize embodied cognitive structures [11, 20] that signal which parameters a representation must preserve. When experts reach for source domains to describe a phenomenon, they externalize embodied cognitive structures [12, 21] that signal which parameters a representation must preserve

4 Parameter Mapping Analyses

We apply parameter mapping to six existing representations, tracing where fidelity is achieved, where it is lost, and where false structure is introduced. We expand four cases that demonstrate distinct modes of correspondence. Each analysis draws on the original authors' published accounts of their representation's design rationale and structural properties.

Visual Sedimentation: Structural Correspondence Through Embodied Metaphor. Visual Sedimentation [8] visualizes streaming data as particles that fall, accumulate, and compact at the bottom of the display, with newer items piling onto older ones. The structural correspondence operates across multiple parameters at once: temporal sequence maps to vertical position; volume of activity maps to pile height; the falling-and-settling behavior maps to the arrival of new events; and the gradual compression of older material maps to the recession of past events from immediate attention. Each parameter of the geological source domain has a behavioral correspondent in the streaming data phenomenon. Viewers do not need to learn what the visualization means because they already know how piles of sand or snow behave. Individual item identity collapses into

Table 1: Parameter mapping analysis applied to six existing representations spanning visualization, sonification, and physicalization.

Representation	Source → Target	Parameter Mapping	Fidelity Gained	Fidelity Lost	False Structure
Visual Sedimentation [8]	Geological deposition → streaming data	time→vertical position; activity→pile height; arrival→falling motion; age→compression	temporal sequence; activity rhythm; volume comparison	individual item identity; categorical structure	older items implied as more permanent or foundational
Heartbeat sonification [4]	Cardiac physiology → auditory stream	*structural:* heart rate→rhythm; fibrillation→signal modulation. *arbitrary:* BP→pitch; temp→filter	embodied recognition (structural couplings only)	fine-grained waveform detail; simultaneous comparison across patients	pitch hierarchy implied as physiological hierarchy
Treemap [9]	Nested containment → hierarchical-quantitative data	hierarchy→nesting; quantity→rectangle area	part-whole structure; proportional comparison (for hierarchical data)	lateral and cross-branch relationships	containment implies hierarchy; sibling proximity implies relatedness (for non-hierarchical data)
ThemeRiver [7]	Fluid flow → thematic change	time→horizontal flow; theme→color band; prominence→channel width	temporal continuity; gradual change; volume comparison	theme content; document identity; abrupt transitions	tributary metaphor implies theme merging or branching
City Metaphor [21]	Urban landscape → software system	class→building; metric→building dimension; package→district	containment; scale comparison; density patterns	dependency relationships; temporal evolution	spatial adjacency implies architectural similarity
Ball-and-stick model [6]	Geometric solids → molecular structure	sphere→atom; rod→bond; angle→bond angle	bonding topology; reactivity; chirality; molecular interaction	electron density; orbital shape; quantum behavior	rigid mechanical bonds implied where electron-sharing dynamics are present

the aggregate accumulation, a deliberate abstraction that is appropriate when the phenomenon of interest is the volume and rhythm of activity rather than any single event. The same technique carries a risk of false structure: streaming data does not become more compressed or foundational with age, and a designer applying the technique to a phenomenon where older items are not meaningfully more "settled" than newer ones would be importing a relationship the phenomenon does not have.

Heartbeat Sonification: Structural vs. Arbitrary Correspondence. As described in §, Fitch and Kramer's ICU monitoring system [4] demonstrates both modes within a single representation. Parameter mapping predicts the divergence the original study documented: the four structural couplings preserved behavioral correspondence between sound and body and required no training, while the four arbitrary couplings had no behavioral correspondence and required memorization. The structural/arbitrary distinction is identifiable at the parameter specification stage, before construction begins. This is what makes parameter mapping a design-time tool rather than a post-hoc evaluation.

Treemap: False Structure. The treemap [9] achieves high fidelity for strictly hierarchical-quantitative data, where proportional part-whole relationships are space-efficient and immediately readable. Apply it to data with non-hierarchical relationships, though, and the treemap's containment structure creates relationships the phenomenon does not have. Software dependencies that cross package boundaries vanish; siblings on different branches appear related by proximity. Ziemkiewicz and Kosara [23] provide the empirical mechanism: viewers infer conceptual relationships from visual structure whether or not those relationships exist in the data. A treemap on non-hierarchical data introduces containment relationships the phenomenon does not have, even if sometimes usefully, as navigational scaffolding, but this is always a structural choice the designer should make deliberately.

ThemeRiver: Partial Structural Correspondence. ThemeRiver [7] visualizes thematic changes in document collections as a river-like flow, with theme prominence mapped to channel width, time mapped to horizontal flow, and theme identity mapped to color band. The structural correspondence draws on viewers' embodied understanding of fluid systems: a thicker channel reads as more volume; the directional flow signals temporal progression without explicit axes; smooth widening and narrowing map to gradual changes in prominence. Where the metaphor strains is at branching and merging events. Themes do not actually flow into or out of one another the way tributaries join a river, and a viewer reading the visualization may infer causal continuity between adjacent bands that the underlying documents do not support. This is partial structural correspondence: the temporal-volume parameters carry fidelity, while the topological adjacency of bands introduces relational structure the phenomenon does not have.

City Metaphor: Deliberate Abstraction Through Spatial Mapping. Wettel and Lanza's software cities [21] map software systems to urban landscapes, with classes as buildings, packages as districts, and software metrics (lines of code, complexity) mapped to building dimensions. The structural correspondence operates through spatial reasoning that viewers bring as embodied common sense: containment relationships are immediately readable, scale comparisons are direct, and density patterns surface clustering structure that would be hard to see in a tree or graph view. The deliberate abstraction is significant. Cities have semantically loaded spatial properties (cardinal directions, traffic patterns, walking distance) that have no software-architectural correspondent, and the metaphor brackets these without loss to the analyses the visualization supports. The risk of false structure emerges when viewers extend the metaphor beyond what is mapped: spatial adjacency between buildings does not imply call-graph adjacency between classes, and viewers familiar with cities may infer architectural similarity from neighborhood proximity that the underlying software does not have.

5 Discussion

The parameter mapping analyzes surface findings that do not include encoding theory and task-based evaluation.

Structural correspondence is critical theory for visualization. HFV's underlying contribution is theoretical as well as methodological. Cognitive science and semiotics have long named structural correspondence as the property that lets representations carry reasoning. Visualization research has approached this property obliquely, through concepts like data abstraction, visual metaphor, and encoding effectiveness, without naming the property itself. We name it here to introduce theoretical access to what its existing tools can surface, and provide a foundation that future empirical work and design methods can build on.

Fidelity is a phenomenon-level property. Encoding theory describes which visual channel best encodes a data type. Parameter mapping investigates whether the representation's structural properties correspond to the phenomenon's structural properties. These questions should be considered separately, as a representation can score well on one while failing the other. While the field has well-developed tools for the first, parameter mapping has the potential to address the second. The two approaches are complementary rather than competing: encoding theory ensures that values are recoverable, while parameter mapping ensures that the representation's structural assertions are warranted by the phenomenon. Fidelity is assessed relative to a stated analytical intent; the same phenomenon may support multiple defensible structural readings, and the framework's contribution is making each reading's commitments explicit.

The structural/arbitrary distinction is assessable at design time. The heartbeat sonification shows that whether a parameter mapping is structural or arbitrary is a property of the mapping itself rather than a judgment of taste. Structural mappings produce intuitive correspondence; arbitrary mappings require memorization. The distinction can be assessed at the parameter specification stage, before construction, and can produce many suitable design alternatives from the same logic. This places parameter mapping at the analytical end of the design process, when many candidate representations are still under consideration.

False structure is a distinct failure mode. Current evaluation methods detect when a representation fails to encode something, however they are less equipped to detect when it encodes something false. The treemap case shows this: containment imposes hierarchy the phenomenon does not have, and viewers read the imposed relationships as meaningful [23]. Parameter mapping surfaces this kind of failure by asking two questions of every parameter: what does it carry, and what does it introduce? The latter question is novel to the framework and identifies a class of design problems that current evaluation methods bracket.

Deliberate abstraction belongs in the design vocabulary. The ball-and-stick model collapses structural correspondence on several dimensions, and that collapse is what makes chemical reasoning possible. The relevant question is whether the representation preserves what matters for the reasoning it needs to support, and whether it avoids introducing what the phenomenon does not have. Our framework gives designers vocabulary to defend or interrogate abstraction choices: an abstraction is deliberate when its parameter omissions can be tied to the reasoning the representation supports, and ungrounded when they cannot.

6 Limitations and Future Work

Parameter mapping presupposes that the structural properties of the phenomenon can be articulated. For phenomena where the structure is contested or partially understood (climate systems, social networks, economic flows), different domain experts may identify different structural properties as load-bearing, and the framework will surface this as substantive disagreement about what fidelity should preserve. We see this as a feature rather than a limitation: parameter mapping makes the latent structural commitments of representational choices explicit, including their domain-dependence. The current framework focuses on relatively static parameter mappings. Empirical validation of HFV is the most pressing direction. Two studies could test the framework: a comparison study of whether designers using parameter mapping make demonstrably different design choices than those using encoding theory alone, and a perception study testing whether viewers interpret representations developed with high fidelity scores more accurately than those developed without it. Both extensions support the methodology-level claim that fidelity is an assessable property of representations distinct from perceptual accuracy or encoding correctness.

7 Conclusion

We have named structural correspondence critical theory for visualization design, defined fidelity as structural correspondence at the parameter level, and proposed parameter mapping as the analytical tool to assess it. Applied to six representations spanning visualization, sonification, and physicalization, the analyses reveal patterns of deliberate abstraction, of structural versus arbitrary coupling, and of false structure that current methods do not surface. We offer the framework as a theoretical contribution at the methodology-level with empirical validation reserved for future work.

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