

Towards a Framework for Collaborative Design of Science Visualisations in Heritage Contexts

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DOI Link: <http://dx.doi.org/10.6007/IJARBSS/v15-i12/27220>

Published Date: 10 December 2025

Abstract

Heritage sites are increasingly adopting information visualisations to communicate complex scientific knowledge, such as paleontological, archaeological, and ecological content, to diverse public audiences. Despite this trend, there remains a lack of structured guidance for collaborative design processes that involve scientists, designers, and educators, often leading to visualisations that prioritise either scientific accuracy or aesthetic appeal at the expense of audience comprehension. This paper addresses this gap by proposing a simplified co-design framework derived from semi-structured interviews with experts in palaeontology, museum education, and visual design. The framework outlines five key phases: goal articulation, stakeholder mapping, prototype visualisation, iterative user feedback and refinement, and public deployment. Emphasis is placed on cognitive accessibility, incorporating strategies such as scaffolding, visual metaphors, clear hierarchical structures, and multilingual support. By integrating participatory collaboration with audience-centred design principles, the proposed model provides a practical guide for heritage institutions seeking to optimise both comprehension and engagement in scientific visualisations.

Keywords: Co-Design Framework, Science Communication, Heritage Visualisation, Stakeholder Collaboration, Design Methodology

Introduction

Effective communication of complex scientific and cultural knowledge remains a central challenge for heritage institutions, environmental communication, and science education. As public understanding increasingly relies on mediated representations, the ability to translate technical data into comprehensible and engaging visual forms has become critical for improving scientific literacy, fostering public trust, and supporting evidence-based decision-making. This need is especially urgent in heritage and environmental domains, where misunderstanding of scientific information can limit public appreciation, weaken conservation support, or hinder informed participation in sustainability initiatives. Although advances in digital technologies have expanded the capacity of information visualisation

(InfoVis) to act as a bridge between experts and the public (Butdisuwan et al., 2024), the gap between scientific complexity and audience comprehension persists, revealing a fundamental communication problem that requires systematic investigation.

Paleontological heritage exemplifies this challenge. Fossil sites embody deep-time evolutionary, ecological, and geological narratives that are central to understanding biodiversity, environmental change, and planetary history. Yet these narratives are conceptually distant from everyday experience and are often communicated through abstract scientific models that overwhelm non-specialist audiences. Improving public comprehension of such knowledge is essential not only for heritage appreciation but also for strengthening public engagement with broader issues such as extinction, conservation, and climate change. Consequently, developing more accessible and cognitively supportive visualisation strategies carries significant social, educational, and institutional value.

This study examines how schema theory and co-design methodologies can enhance InfoVis design to improve cognitive accessibility and engagement. Schema theory explains how individuals interpret new information by linking it to existing knowledge structures (Meylani, 2024), while co-design involves participation from experts, educators, and public users to ensure that visualisations are relevant, intuitive, and inclusive (Sin et al., 2022). Integrating these approaches moves InfoVis beyond aesthetic or technology-driven experimentation toward evidence-based design grounded in cognitive science and user needs. Such integration is beneficial for museum practitioners, designers, educators, and policymakers seeking effective tools to communicate complex scientific narratives to diverse publics.

The Chengjiang Fossil Site—a UNESCO World Heritage property renowned for its early Cambrian biota—provides an ideal context for testing these approaches. Its intricate narratives pose well-documented comprehension challenges for visitors, revealing a clear need for more supportive communication tools. Complementarily, the 2024 CHINAVIS Information Visualisation Design Exhibition offers access to design-trained audiences whose engagement patterns provide insights into professional expectations for clarity, structure, and innovation. Together, these settings enable a comparative analysis of how scientific, design-oriented, and general audiences interact with InfoVis systems aimed at balancing accuracy, engagement, and accessibility.

A mixed-methods design within a design-based research (DBR) framework was employed, integrating literature review, case documentation, field observation, expert interviews, focus groups, and structured questionnaires at both CHINAVIS and the Chengjiang Museum (December 2024–February 2025). This triangulated approach strengthens methodological rigour and captures insights from both professional and non-professional perspectives.

The study pursues three objectives: (1) to examine public perceptions and cognitive challenges in understanding paleontological visualisations, (2) to evaluate the effectiveness of schema-informed design in enhancing clarity and engagement, and (3) to develop and validate a co-design framework that integrates cognitive principles with participatory design for sustainable science communication. The proposed framework has broader significance

beyond palaeontology; it offers a transferable model for environmental communication, corporate sustainability reporting, and public health education. By improving the accessibility and inclusivity of scientific communication, the study contributes to more informed publics and supports UN Sustainable Development Goals 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production).

Literature Review

Effective science and heritage communication relies increasingly on information visualisation (InfoVis) to translate complex data into accessible and engaging formats. InfoVis enables audiences to understand abstract concepts—such as evolutionary processes, ecological networks, or geological timelines—through visual structures that reduce cognitive load and support pattern recognition (Sweller, 2022). Research demonstrates that well-designed visualisations enhance comprehension, retention, and affective engagement, particularly when aligned with viewers' cognitive capacities (Maier, 2025). However, the challenge lies in balancing scientific accuracy, aesthetic appeal, and cognitive accessibility for heterogeneous audiences, including experts, students, and the general public (Xu et al., 2025).

Cognitive theories provide a foundational lens for addressing these challenges. Schema theory, rooted in cognitive psychology, explains how individuals process and interpret new information by integrating it with existing knowledge structures (Meylani, 2024). In visual communication, schema-informed design aligns complex content with familiar hierarchies, sequences, and patterns, facilitating comprehension while reducing cognitive overload. Dual coding theory further underscores the value of multimodal representation, highlighting the synergistic effect of combining visual and verbal information to enhance learning and memory (Li et al., 2022). These theoretical frameworks suggest that effective InfoVis should not merely present data but structure it to reflect the audience's cognitive schemas.

Participatory design and co-design approaches have gained traction in heritage and science communication. Co-design actively involves stakeholders—scientists, educators, designers, and end-users—in iterative development cycles, ensuring that visualisations meet both epistemic and experiential needs (Kerr et al., 2022). Studies in museum and heritage contexts indicate that co-created exhibits increase accessibility, relevance, and audience engagement by integrating expert knowledge with user feedback (Massari et al., 2024). Despite these advances, research on the systematic integration of schema-informed design within co-design frameworks for heritage visualisation remains limited, particularly for complex scientific content such as paleontological narratives.

Recent work in digital heritage and design exhibitions highlights the potential of interactive and multimodal tools—including 3D reconstructions, augmented reality (AR), and dynamic timelines—to facilitate cognitive and emotional engagement (Lin et al., 2025). Evidence suggests that layering information, providing contextual narratives, and offering multilingual support further enhance comprehension across diverse audiences (Shifrina-Piljovin, 2025). Comparative studies also reveal that design professionals often prioritise aesthetic coherence and innovation, whereas the general public values clarity, narrative flow, and immersive realism, emphasising the need for adaptable and audience-sensitive design strategies (Bruno & Tagliasco, 2022).

Taken together, the literature underscores the importance of integrating cognitive theory with participatory design to bridge the gap between scientific complexity and public understanding. However, structured frameworks guiding the collaborative creation of schema-informed visualisations remain scarce. This gap motivates the present study, which seeks to develop a co-design framework that combines cognitive accessibility, iterative stakeholder engagement, and multimodal visualisation principles, enabling heritage institutions to communicate complex scientific content effectively to diverse audiences.

Materials and Methods

This study employed a mixed-methods design within a Design-Based Research (DBR) framework, which facilitates iterative cycles of analysis, design, implementation, and reflection to link theory, practice, and empirical evidence (Tinoca et al., 2022). DBR guided the integration of schema theory, information visualisation (InfoVis), and co-design methodologies to develop a framework for communicating complex paleontological knowledge. The research process combined conceptual exploration of theoretical literature, empirical data collection from public participants and experts, iterative prototyping of visualisations, and synthesis to refine the co-design framework.

Data were triangulated to enhance validity and reliability, drawing on literature review, longitudinal field observations (2022–2024), focus group discussions with interdisciplinary experts, semi-structured interviews with thirteen professionals in palaeontology, museum studies, and design, and public questionnaires administered at the CHINAVIS 2024 exhibition and the Chengjiang Fossil Site Museum (December 2024–February 2025). The public sample comprised 464 valid responses, including design students, lecturers, professionals, and general museum visitors, providing a comparative lens on the influence of prior knowledge and expertise. Experts were selected purposively to ensure disciplinary diversity and informed validation of the co-design framework.

The questionnaire combined Likert-scale items and open-ended questions, measuring comprehension, engagement, accessibility, and design appeal. A pilot test with ten respondents established reliability (Cronbach's $\alpha = 0.87$) and informed refinement of item wording and sequence. Expert interviews and focus groups explored cognitive accessibility, interdisciplinary collaboration, and visual communication challenges. At the same time, field observations captured visitor behaviour and engagement patterns, including moments of confusion or extended interaction with visualisations.

Quantitative data were analysed using descriptive statistics and comparative tests to identify differences between CHINAVIS participants and Chengjiang visitors, revealing higher comprehension among design-trained respondents and varying engagement patterns across audiences. Qualitative data—including open-ended responses, interviews, and observation notes—were thematically coded to identify cognitive challenges, design effectiveness, and engagement mechanisms, allowing integration of public perception with expert insight (Lim, 2025).

Ethical approval was obtained from the affiliated institution, with all participants providing informed consent and responses anonymised to ensure confidentiality.

Trustworthiness was further strengthened through triangulation, member checking, and reflexive documentation to mitigate bias.

This methodological approach enabled the iterative development of a schema-informed co-design framework, ensuring alignment between cognitive theory, visual design principles, and participatory stakeholder input. It provided a robust basis for comparing audience responses, validating design prototypes, and generating actionable insights for effective science and heritage communication.

Results and Discussion

Data from the CHINAVIS 2024 exhibition and the Chengjiang Fossil Site Museum provided complementary perspectives on audience interaction with complex scientific visualisations. CHINAVIS participants were primarily design-trained professionals and students, while Chengjiang visitors represented a heterogeneous general public. This dual-site comparison enabled the study to examine how disciplinary familiarity, prior knowledge, and visual literacy influence comprehension, engagement, and interpretive confidence. Quantitative data ($n = 464$) were integrated with qualitative insights from open-ended responses, field observations, and expert interviews to explore cognitive accessibility, emotional engagement, and design evaluation.

CHINAVIS respondents reported higher comprehension and confidence in interpreting scientific visualisations, with mean differences of 0.8–0.9 points across dimensions such as understanding evolutionary relationships and accessibility of visual information. This reflects the moderating role of pre-existing cognitive schemas, as design-trained audiences could decode visual metaphors—such as hierarchical diagrams and ecological flow maps—more effectively than general visitors. Qualitative responses indicated that CHINAVIS participants linked visual patterns to existing frameworks, whereas Chengjiang visitors often struggled with abstract representations, relying instead on surface cues like colour or scale. Field observations corroborated these findings: museum visitors paused frequently at complex, text-heavy panels but engaged longer with narrative-based or immersive displays, highlighting the importance of scaffolding and schema-aligned design to reduce cognitive load (Wang et al., 2025).

Engagement patterns diverged between the groups. CHINAVIS participants demonstrated analytical engagement, focusing on data layers, structural coherence, and interactivity, whereas Chengjiang visitors exhibited strong emotional and narrative engagement, responding to storytelling and immersive elements. Despite lower comprehension, general audiences rated aesthetic appeal and emotional connection higher, supporting dual-channel processing theories in which affective resonance can facilitate interest and retention (Panteli et al., 2025). Narrative-driven visualisations helped lay audiences link new information to familiar temporal and causal frameworks. In contrast, expert audiences prioritised visual logic and design clarity, illustrating the need for dual pathways accommodating both analytical and affective cognitive styles.

Expert validation reinforced these insights. Thirteen professionals in palaeontology, museum studies, and design emphasised the importance of modular, hierarchical, and interactive information structuring, aligning with schema theory principles such as chunking

and hierarchical organisation. Bilingual integration further supported comprehension and dual coding, enhancing accessibility for diverse audiences. Experts confirmed that progressive disclosure and layered visualisation effectively balance scientific fidelity with public engagement, bridging cognitive and disciplinary gaps.

Integrating these findings, the study highlights the central role of schema alignment in effective science communication. Visual abstraction and symbolic compression support audiences with pre-existing schemas, while metaphors, narrative cues, and scaffolding facilitate schema construction for lay audiences. The co-design process acted as a "cognitive mediation platform," enabling iterative collaboration between scientists, designers, and educators to embed cognitive accessibility into visual prototypes (Worsley & Bar-El, 2022). Hierarchical visualisation strategies, mapped onto the DIKW model, allow audiences to progress from foundational understanding to deeper exploration, supporting both learning and engagement (Lo Duca & McDowell, 2025).

Overall, the results indicate that schema-informed co-design enhances cognitive accessibility, fosters emotional resonance, and transforms museum communication into a participatory knowledge co-creation process. By aligning design with audience schemas and integrating iterative feedback, the approach offers a scalable, empirically grounded model for improving public comprehension of complex scientific information while balancing analytical clarity and affective engagement.

Conclusion

This study examined how integrating schema theory and information visualisation (InfoVis) within a co-design framework can enhance the communication of complex paleontological knowledge, using the Chengjiang ancient biota as a case study. Employing a mixed-method design—including literature review, longitudinal fieldwork, public surveys (n = 464), and expert consultations—the research produced a schema-informed co-design framework that aligns visual representation with audience cognitive structures. Findings revealed that comprehension is strongly mediated by pre-existing schemas, with design-trained CHINAVIS participants demonstrating higher interpretive confidence than general public visitors at Chengjiang, who relied more on narrative cues and emotional engagement. Iterative expert validation confirmed the value of layered hierarchies, bilingual content, and narrative immersion in bridging scientific accuracy and accessibility.

Theoretically, the study extends schema theory from a cognitive construct into a design logic, operationalising principles such as scaffolding, chunking, and hierarchical organisation in InfoVis. Integrating co-design with cognitive science reframes stakeholder participation as cognitive mediation, where designers, scientists, and audiences collaboratively negotiate meaning. This approach advances science communication scholarship by providing a cognitively grounded, inclusive framework for translating complex data, moving beyond traditional models focused solely on content accuracy.

Practically, the research demonstrates that hierarchical, schema-informed design enhances both comprehension and engagement. Layered interfaces, progressive disclosure, colour coding, and interactive features allow audiences to build understanding incrementally. Emotional design—through narrative, soundscapes, and speculative prompts—fosters

engagement and retention, particularly for non-specialist audiences. The co-design process itself proved a sustainable method for interdisciplinary collaboration, producing communication artefacts that are contextually grounded, evidence-based, and socially inclusive.

Policy and institutional implications are significant. Museums and heritage organisations can adopt schema-informed protocols to evaluate and improve interpretive materials, train educators to anticipate audience cognition, and embed participatory design practices into exhibition development. In academic and professional contexts, the model provides a pedagogical tool for cultivating audience-centred design and science communication skills. Governance bodies and funding agencies may further institutionalise these principles to support iterative, participatory, and cognitively grounded public outreach initiatives.

Limitations include the geographically and culturally specific sample, reliance on self-reported and observational data, and focus on palaeontology. Future research could explore broader scientific domains, incorporate physiological or eye-tracking measures, and investigate AI-assisted adaptive visualisation to align content with user schemas dynamically. Such approaches would further personalise and optimise cognitive engagement in InfoVis applications.

In conclusion, this study demonstrates that effective science communication depends not merely on aesthetic or technological sophistication but on aligning visualisation with human cognition and affect. Schema-informed co-design offers a robust, scalable model for bridging disciplinary knowledge and public understanding, fostering intellectually rigorous, emotionally resonant, and socially inclusive experiences. By integrating cognitive principles, participatory collaboration, and visual communication, heritage and scientific institutions can empower audiences to engage critically with complex scientific narratives, enhancing both comprehension and long-term engagement with the natural world.

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