Designing Digital–Physical Visualization Environments for Co-Located Collective Decision-Making

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Summary: This project investigates novel digital-physical visualization environments for diverse audiences collaboratively exploring and discussing complex data for public decision making. Example scenarios include urban planning, climate mitigation, and general civic participation. Because these decisions affect society at large, meaningful progress depends on broad participation and the exchange of data, interpretations, and perspectives. While data provides a foundation for evidence-based dialogue, data about such problems is often complex, large, and multidimensional. Through iterative prototyping and user-centered research, the project will explore different data visualization environments for (primarily) co-located synchronous collaboration—potentially including large interactive wall displays, tangible or physical data representations, mixed-reality or immersive collaborative setups. We will begin by defining a design space for such spaces, followed by the development of prototypes across different formats. Prototypes will be evaluated through controlled lab studies and refined into more mature systems for real-world field studies on collaborations. These studies will be helped by our partners such as the Edinburgh Climate Change Institute, NASA's visualization studio, and the data team at Bordeaux Métropole. The project will synthesize its findings into design guidelines, techniques, and potentially toolkits for future collaborative visualization environments.

Research Group: Bivwac is a joint research team between Inria (Université de Bordeaux) and the CNRS (LaBRI) that aims to bridge the gap between complex data and public understanding through immersive visualization experiences. It explores how combining data, visual, and experiential elements (e.g., VR, AR, tangible and physical interfaces) can make abstract phenomena—such as environmental issues, mental health, or advanced science—more accessible and engaging for non-experts. By studying the role of immersion, interactivity, and collaboration in learning, and focusing on domains aligned with the United Nations Sustainable Development Goals, Bivwac seeks to improve understanding, reduce misconceptions, and support more informed individual and collective decisions.

Disclaimer: *This proposal is a revised version of a PhD project originally submitted under the PEPR eNSEMBLE AAP2 call as part of the CollEcTIVE proposal: Collaborative Environments to Engage with Wicked Topics through Interactive Visualization Experiences. Following our invitation to the stage 2 interviews in February, we are still awaiting a funding decision. This application reflects our intention to continue advancing the research around the topics outlined in CollEcTIVE; should the project be funded, we will withdraw this PhD application.*

DESCRIPTION OF DOCTORAL PROCESS

Context

Collaboration is essential for tackling contemporary public decision-making processes in the context of, e.g., the environmental crisis [Hartman2002] or economic inequality [Millard2023]. Such decisions are often characterised as *wicked* problems that have unclear definitions, no single solution, shared responsibilities [Rittel1973], and are sometimes time-sensitive and evolving [Levin2012]. Because these problems affect all of humanity, diverse groups must collaborate to *"exchange data, interpretations, and perspectives and gain understanding of mutual dependencies, various problem perspectives, and alternative solutions"* [Hartman2002].

This project focuses on data-centered collaboration to address problems where data serves as evidence for debate and decision-making; data enables describing the past, monitoring the present, modeling futures [Sudmant2024], and representing local knowledge. Yet barriers remain: data is often complex, uncertain, incomplete, and inaccessible or unintelligible to non-experts [Raaphorst2020]. Without integrating data into shared processes, decision-making remains poorly informed, producing ineffective outcomes [Sturge2022].

Unlike most research on collaborative data visualization environments, which targets experts with shared problem knowledge, our challenge is to enable a wide range of participants to engage with data, exchange ideas, and deliberate. Interfaces must support diverse users—policy advisors, NGOs, businesses, citizens, and researchers—who may have little experience with data analysis or advanced visualizations, ensuring that unheard or marginalized voices can also contribute. Success means fostering communities with a shared understanding of the problem and potential solutions—a crucial step toward addressing wicked problems.

Objective and Research Questions

The goal of this PhD project is to develop visualization environments and experiences that support diverse audiences in co-located settings using digital visualization technologies, including prototypes for explanation, onboarding, data creation, exploration, and deliberation. Research questions include:
[R1] *What makes an environment effective for co-located collaborative engagement with data?*
[R2] *How can participants be guided, onboarded and the data explained effectively?*
[R3] *How does co-location and physical situatedness influence collaboration, understanding, and deliberation?*
[R4] *Which types of visualization environments (e.g., large displays, immersive systems, data physicalizations, hybrid configurations) are best suited for specific collaborative activities such as exploration, annotation, negotiation, or decision-making?*

Brief state of the art

Collaboration enhances learning compared to individual study, especially for complex tasks like wicked problems [Dillenbourg2009]. For instance, in quantum mechanics—a notoriously difficult subject—students working together solved problems that none could solve alone [Brundage2023]. Collaboration also acts as an *action lever*, leveraging input from diverse stakeholders, unlike top-down approaches that can exclude participants and viable solutions [Murphey1997]. It fosters learning about issues, methods, and solutions, and builds networks beyond the initial problem [Clarke1999]. Wicked problems are global but require inherently local solutions—engaging local stakeholders, incorporating their knowledge, and adapting solutions to local contexts while supporting global exchange. Psychological distance can further hinder progress: problems like climate change often feel remote, reducing concern and action [Spence2012]. Co-located and remote collaboration can bridge this distance, connecting participants to the problem, each other, and potential solutions. However, no platform currently supports direct visualization and deliberation with data [Frappier2024]. This PhD project aims to bridge this gap to explore how collaborative visualization experiences can improve understanding and action, compared to individual or non-data-driven collaboration.

Data visualization aims to reveal patterns and communicate complex insights [Munzner2025], including for climate data [Kostis2025]. Collaborative visualization is defined as *“the shared use of computer-supported, (interactive) visual representations of data by more than one person with the common goal of joint information processing”* [Isenberg2011]. Research has explored beyond-desktop collaborative visualization platforms such as tabletop displays

[Isenberg2011], wall displays [Leon2025], mixed reality [Cordeil2016; Assor2024], and data physicalizations [Sauvé2023]. Recent initiatives on multimodal remote and hybrid collaboration for data analysis and decision-making [Büschel2025; Brehmer2024] identify open questions, but focus mainly on remote settings. Moreover, most prior work targets homogeneous mostly domain-expert groups with shared goals and understanding or challenges for remote collaboration with visualization [Brehmer2026]. In contrast, this proposal emphasizes heterogeneous, inclusive groups in co-located data-heavy tasks and environments.

Approach and methods

This project employs iterative design, co-design and prototyping as well as user-centered evaluation such as quantitative and qualitative evaluation, interviews and observations. (1) We will start **devising a design space** based on our own experience and a structured literature review (M1-M6). (2) Together with our project partners (see below) we will then engage in understanding and **defining collaborative activities**, through interviews and focus groups (M3-9). (3) We will then **develop innovative prototypes**, potentially including large interactive wall displays for collective exploration, tangible or physical data representations, mixed-reality or immersive collaborative setups, hybrid configurations combining physical artifacts and digital augmentation. These systems will be designed to support concrete collaborative tasks as identified in (2, such as explaining complex datasets, discussing questions, scrutinizing data, or structuring deliberation). We design prototypes through iterative design and development including low and high-fidelity prototyping, co-design sessions with our experts and early feedback, pilots, and eventually controlled usability studies. Prototypes will be developed, implemented, and evaluated in our lab first during year 1 (M9-M24), and (4) **deployed and tested in real-world scenarios** with our partners in year 3 (M25-M30). Deploying in the field will allow us to study collaboration behavior, learning with data, and deliberation processes with data. (5) The final months of this project (M31-36) will see a **synthesis and discussion** of studies, design guidelines, and eventual design toolkits. The project is supported by external partners contributing data, expertise, and real-world use cases. **Bordeaux Métropole (Data Office)** will provide open datasets and public engagement contexts, building on ongoing collaborations. The **Edinburgh Climate Change Institute** will contribute socio-economic climate modeling data and apply its models to selected French communities. The **NASA Scientific Visualization Studio** will provide advanced Earth science visualizations, including the Earth Now Dashboard for large public displays.

Evaluation of contributions

From the beginning, this project follows an interactive user-centered design process. We engage with our partners and their collaborative scenarios, assuring ecological validity of our research. For evaluation of our techniques, we will rely on mixed-methods approaches, gradually transitioning from in-the-lab to in-the-wild setups. During the early phase, we will study our prototypes with a strong focus on usability (how people interact with an environment and technique, which barriers they encounter, what they have to learn). To this end, we employ think-aloud walkthroughs, interviews and subjective assessments to specific questions. Study tasks can vary from specific interaction tasks to more open-ended tasks involving exploration and understanding of complex data and visualizations. In the later process and once usability is established, we will shift evaluation towards collaboration and how our prototypes support collaboration among co-located participants. To study collaboration, we will rely on field evaluations, deploying visualization environments in public and semi-public spaces. We will employ a similar qualitative-observational framework to understand collaboration behavior (inter-person interaction), collaboration content (e.g., discussion, decisions, understanding), as well as interaction with the collaborative environment (who does what, how often). These observations will lead to a multi-faceted

understanding—both quantitatively and qualitative—of collaboration with digital-physical visualization environments.

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NATURE OF DIGITAL COLLABORATION

Function: The collaboration centers on collective sensemaking and deliberation with data, where participants jointly explore, scrutinize, and interpret complex datasets, question assumptions, compare perspectives, and progressively build a shared understanding to support discussion and decision-making around wicked problems.

Type: It is a synchronous co-located collaboration around shared visual and interactive artifacts (e.g., large displays, physicalizations), where participants explore, discuss, and react together. There are cases where collaboration needs to be complemented by longer-lived interactions such as revisiting data, adding interpretations, or continuing discussions across sessions. While not the main focus of this project we will consider, investigate, and discuss how the environments we envision can support long-term, asynchronous collaboration, especially between participants who do not meet each other.

Time scale: Collaboration unfolds at multiple nested scales: immediate interactions during a session (e.g., exploring or debating data in minutes to hours), embedded within longer participatory processes (e.g., workshops, public exhibitions, or policy discussions over weeks or months) tied to evolving issues with potentially unforeseen twists.

Group size: The project targets heterogeneous groups of stakeholders, typically small to medium-sized groups (2-10, e.g., mixed participants like citizens, experts, policymakers) engaging directly together, while also accommodating larger public audiences in open or semi-public settings.

Space: The collaboration is designed for physically shared environments augmented with digital components (e.g., wall displays, tangible artifacts, mixed reality), enabling participants to gather around shared representations, while also supporting hybrid extensions where some elements or participants may be distributed.

CONTRIBUTION TO DIGITAL COLLABORATION: EXPECTED RESULTS AND IMPACT

We contribute **empirical insights** into how collaborative understanding, learning, and deliberation unfold, particularly how diverse audiences achieve shared comprehension of complex data through physical-digital visualization environments. The impact of design and technology choices on behavior will be formalized in guidelines and theoretical frameworks, aiming to demonstrate that a culture of data-driven deliberation enhances decision quality and public trust.

The project advances **theory** by proposing design spaces, concepts or frameworks to design and digital-physical environments and to explain how digital collaboration works in these environments.

The project will contribute **techniques, prototypes**, (and potentially toolkits) for participatory visualization environment and will introduce novel designs addressing key HCI and visualization challenges. These designs will be rigorously evaluated and published in venues such as ACM CHI, IEEE VIS, and ACM CSCW, and documented as adaptable blueprints to support replication and iterative improvement across diverse hardware setups.

In summary, by empowering the public to collaboratively engage with complex data, we expect the project will foster understanding of wicked problems and complex data, advance data and visualization literacy, and better equip people to address 21st-century challenges in evidence-based ways.

POSITIONING WITHIN THE ENSEMBLE PROGRAM

This project is generally aligned with eNSEMBLE's vision for fast, large-scale collaboration and seeks a paradigm shift: from institutional data control—where select bodies own and interpret data—to open collaboration based on shared and trusted information. This proposal targets the important, underexplored intersection of data visualization, wicked problems, and collaboration.

This project further aligns well with the PC1 call by advancing collaborative environments for heterogeneous users and extending beyond expert-focused systems to include diverse, non-expert participants. It is particularly strong with respect to Axis 4 (transitions between collaborative spaces), as it explores how users move across visualization modalities, contexts, and roles. It also contributes to underrepresented areas in other axes: examining embodiment and representation in immersive environments (Axis 2) and addressing multi-stakeholder collaboration in complex scenarios (Axis 3). Finally, the project offers strong potential for impact through demonstrators and design guidelines developed with academic and institutional partners, in line with the call's emphasis on dissemination and practical outcomes. Several already funded PhD topics strongly align with the proposal, particularly those focused on collaborative hybrid environments (AR/VR/tangible systems) and transitions between collaborative spaces. However, none of these projects specifically addresses data visualization or civic deliberation. None of the supervisors has obtained previous funding from the PEPR eNSEMBLE.