Making Complex Workflows Tangible: Investigating Immersive Analytics Approaches for Data Analysis Workflows

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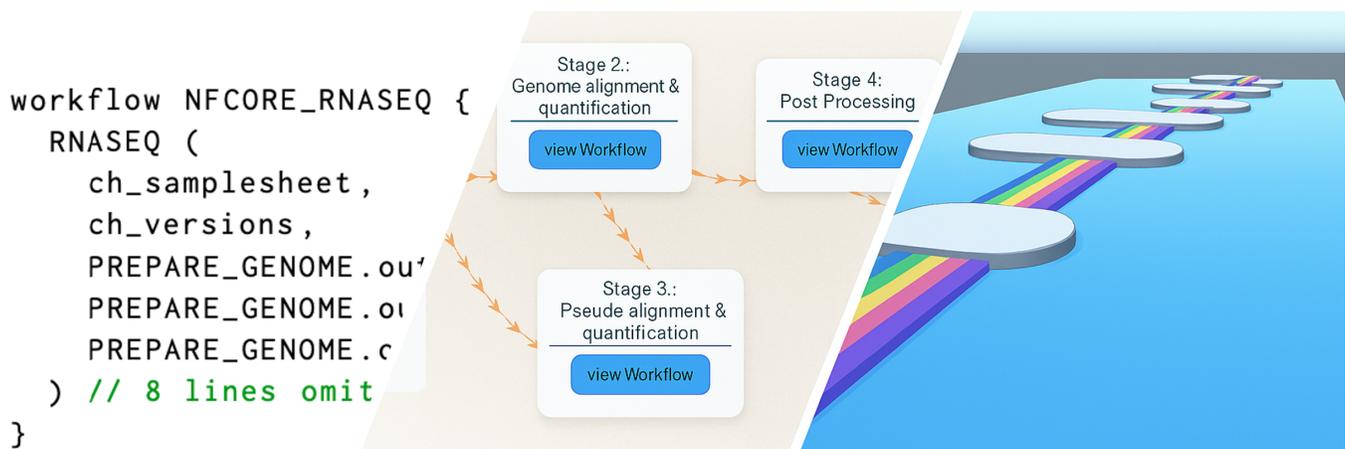thomas.kosch@hu-berlin.de

Figure 1: Data Analysis Workflows (DAWs) are often highly complex, consisting of numerous interdependent steps encoded in domain-specific programming languages. Immersive Analytics (IA) environments offer new potential to support comprehension, exploration, and communication by bringing these workflows into spatial, interactive environments.

Abstract

Data Analysis Workflows (DAWs) are central to modern scientific research, yet their growing complexity presents significant usability challenges. Traditional desktop-based visualizations often lack the spatial and interactive affordances needed to support intuitive understanding and engagement. This study investigates the potential of Immersive Analytics (IA) to improve the visualization and interaction with DAWs. We developed two IA prototypes and tested them in a within-subject user study (N=18), collecting qualitative feedback and evaluating it through a systematic approach. Participants generally found the immersive environments intuitive and enjoyable, highlighting IA's potential to support complex workflow interpretation and communication. At the same time, they noted several limitations, ranging from difficulties in navigation to occasional information overload. These findings emphasize both the promise and the challenges of using IA for DAWs. Together, these insights inform future work on developing mature IA tools capable of supporting diverse scientific practices.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**.

Keywords

Data Analysis Workflows, Scientific Data, Augmented Reality, Virtual Reality, Immersive Analysis, Visualization

1 Introduction

Scientific discovery is becoming increasingly data-driven, with researchers relying on ever-larger datasets to generate insights and

validate hypotheses [11]. To handle this complexity, Data Analysis Workflows (DAWs) have become a cornerstone of modern research practice. A DAW defines a structured sequence of computational steps for automating data processing, transformation, and visualization [19]. Figure 2b illustrates a well-established example. By encapsulating individual processing stages, DAWs promote efficiency, repeatability, and reproducibility in the field of data analysis [21].

Despite these advantages, DAWs remain difficult to use and to communicate between researchers. As DAWs increase in size and structural complexity, researchers face growing challenges in modeling, understanding, and effectively working with these workflows. DAWs often represent more than just computational artifacts, aiding researchers as conceptual models that must be explored, inspected, explained, and adapted over time. Existing representations typically confine these activities to limited two-dimensional screens, which can restrict how users perceive workflow structures.

DAWs are used in multiple natural science fields, such as chemistry, geography, and physics. Typical users include graduate students and domain scientists who may not have formal training in software engineering or data infrastructure. As a result, the steep learning curve and limited interaction support hinder their scientific progress, making this complexity a significant barrier to adoption and collaboration [2, 15, 24]. Yet, while significant effort has been dedicated to developing and refining DAWs, comparatively little focus has been placed on how different interactive representations of workflows influence users' comprehension, usability, and engagement.

At the same time, research in Human-Computer Interaction (HCI) has demonstrated that complex data analysis can benefit from novel visualization techniques, such as those offered by Immersive Analytics (IA) [7]. IA builds upon human spatial cognition and embodied interaction to support understanding of abstract or complex structures. By distributing information in space and allowing direct manipulation, IA potentially enables cognitive offloading and improved sensemaking in ways that flat visualizations often cannot.

From the perspective of pervasive displays, IA systems can be understood as spatially embedded display infrastructures that integrate digital information into users' physical or immersive environments. With the immersive nature of both Virtual Reality (VR) and Augmented Reality (AR) devices (both of which fall under the broader category of XR technologies [17]), IA therefore also potentially enables spatial and interactive representations of workflows. AR-based IA can anchor workflow representations directly in the physical environment, while VR-based IA creates fully immersive spatial displays that surround the user. Both approaches align with the notion of pervasive displays as systems that engage users through spatial, embodied, and often exploratory interaction. These immersive approaches open new possibilities for making data analysis more comprehensible and accessible to a wider range of researchers [9, 13]. Yet, previous research did not investigate to what extent IA can be a helpful asset when working with DAWs specifically.

This motivates a comparative exploration of two immersive workflow visualization approaches that differ in how already existing DAW diagrams and visualizations are spatially embedded and interacted with, investigating how the use of IA tools could affect user comprehension, usability, and engagement when interacting with DAWs. In this paper, we aim to answer this research question by presenting the two prototypes **DAW Grabber** and **DAW Walker**, which bring existing DAW diagrams into immersive environments using AR and VR, respectively. Through a within-subject user study (N=18), we explore how these XR-based IA tools affect user comprehension, usability, and engagement when interacting with complex DAWs.

> **Contribution Statement:** (1) We present two IA prototypes for DAW visualization that explore distinct interaction paradigms; (2) we report the findings from a user study showing the four aggregate dimensions that emerged after a systematic qualitative analysis of participant answers; and (3) we discuss design considerations for future IA tools that aim to support data-driven scientific discovery through more accessible and user-centered DAW interaction.

2 Related Work

To contextualize our work, we review two main areas of related work. First, we examine existing approaches to working with DAWs. Second, we draw on research from the field of IA, particularly studies that explore how XR can support data visualization, navigation, and interaction in complex analytical tasks.

2.1 Working With Data Analysis Workflows

DAWs are structured, often modular processes used to manage complex data analysis tasks in modern, data-intensive research projects [16]. They help formalize and automate sequences of computational steps such as data preprocessing, transformation, modeling, computation, and visualization. DAWs are essential in domains where reproducibility, scalability, and collaboration are important, such as bioinformatics and environmental science.

For a long time, there was no shared or standardized definition of what constitutes a DAW. Instead, individual research communities developed their own workflow models and tooling, tailored to their specific scientific questions and computational infrastructure. This led to the emergence of numerous domain-specific workflow languages and systems, such as Nextflow, Snakemake, and Galaxy [12]. While powerful, these systems often come with steep learning curves and idiosyncratic syntax that researchers must learn in order to effectively design, execute, or interpret DAWs within their domain.

Most researchers dedicate their careers to developing deep expertise in their specific scientific disciplines. However, effectively working with DAWs typically also requires proficiency in programming, familiarity with command-line interfaces, version control, and knowledge of distributed or cloud-based computing infrastructures [5]. For many domain scientists, especially those without formal training in computer science, these additional skill requirements pose a significant barrier to entry. Requiring researchers to

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[2]https://github.com/nf-core/rnaseq/blob/3.20.0/main.nf, last accessed on 2026-01-16.
[2]https://nf-co.re/rnaseq/, last accessed on 2026-01-16.

```
1  workflow NFCORE_RNASEQ {
2    // 50 lines omitted
3    RNASEQ (
4      ch_samplesheet,
5      ch_versions,
6      PREPARE_GENOME.out.fasta,
7      PREPARE_GENOME.out.gtf,
8      // 12 lines omitted
9      PREPARE_GENOME.out.splicesites
10   )
11   emit:
12   trim_status = RNASEQ.out.trim_status
13   // 4 lines omitted
14 }
```

(a) Selected parts of the *rnaseq* DAW specification, using the Nextflow workflow system. (Source code available on Github[1])
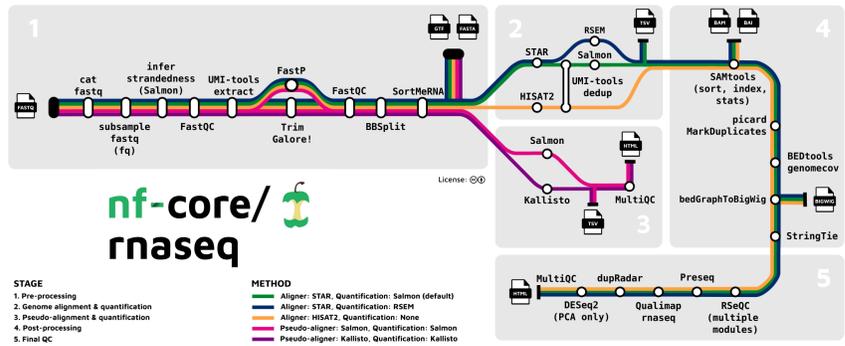
(b) A workflow diagram of the *rnaseq* DAW used in this study. (Made by Sarah Guinchard[2] under the MIT license)

Figure 2: DAWs are typically interacted with in one of two ways: either through the underlying code that defines the workflow logic, or via graphical representations, most commonly as directed graphs.

master both the intricacies of their scientific domain and the complexities of computational workflows places an unrealistic burden on them [3].

As a result, DAWs often remain underutilized or poorly understood by the very people they are meant to support. This can lead to inefficiencies, miscommunication, and errors in data processing pipelines, ultimately slowing down research progress [6]. The increasing complexity of workflows, both in terms of their technical execution and conceptual structure, exacerbates this issue, particularly as collaborative, interdisciplinary research becomes more common.

To address these challenges, researchers are beginning to explore new tools, representations, and support strategies that aim to reduce the technical barriers associated with DAWs. Many of these efforts draw on principles from HCI, including visual design, interaction techniques, and cognitive support mechanisms, to make working with workflows more intuitive and accessible [22]. By rethinking how DAWs are presented and interacted with, these approaches aim to support not just expert users, but also novice and interdisciplinary collaborators who may bring essential domain knowledge but lack advanced technical training.

2.2 Immersive Analytics

IA is an emerging field that explores how immersive technologies, such as VR and AR, can be used to support analytical reasoning and data understanding. Building on research in visualization, HCI, cognitive science, and further related fields, IA aims to utilize spatial and embodied interaction to allow users to engage with data in more intuitive and spatially situated ways [7, 8].

Most IA technologies fall under the broader umbrella of XR, as users are no longer limited to flat screens and, more or less, indirect manipulation and input periphery. Instead, data can be explored at scale, manipulated directly using gestures or movement, and contextualized within physical or virtual space. This shift offers potential cognitive benefits such as reduced working memory load, improved spatial reasoning, and increased engagement [1, 18].

Recent research has shown that immersive environments can enhance collaborative data analysis [20], support sensemaking [23], and aid users in navigating complex information structures through embodied interaction [25]. For example, spatial arrangements can be used to show relationships or dependencies between elements, while embodied actions (e.g., walking, pointing, or looking) can be mapped to navigation and interaction functions. These approaches are especially promising for domains where data is inherently structured or procedural, such as in scientific workflows. Yet, the specific challenges and opportunities of applying immersive interaction to DAWs remain underexplored.

A number of recent systems illustrate how immersive environments can support embodied interaction with structured or multivariate data. For example, ImAxes by Cordeil et al. [4] enables users to manipulate multidimensional data visualizations in 3D space using tracked handheld controllers, supporting exploratory analysis through embodied gestures. Similarly, Ground Control by Katins et al. [14] visualizes geospatial data on the physical ground in front of the user, allowing for manipulation and navigation of data structures by physically moving through them. These examples highlight the potential of spatial immersion and embodied interaction to make complex or abstract data more tangible and accessible.

3 Methodology

This study followed a user-centered design approach to explore how IA could support interaction with DAWs. Building on insights from the aforementioned prior work in IA, we designed and developed two XR-based prototypes that bring existing and commonly used workflow diagrams, such as in Figure 2b, into IA environments. To this end, we conducted a hands-on study in which participants explored and interacted with the two XR prototypes. This evaluation was intended to show both practical design feedback and more general patterns of use and perception. Specifically, we aimed to address the following research question:

RQ: How can the use of Immersive Analytics (IA) tools affect user comprehension, usability, and engagement when interacting with Data Analysis Workflows (DAWs)?

3.1 Apparatus

To explore the potential of IA tools for understanding and interacting with DAWs, we developed two distinct XR prototypes. This dual-prototype approach was chosen deliberately to avoid overloading a single interface with too many functionalities and to showcase different paradigms of current related work in immersive interaction research. Each prototype was inspired by prior work in the IA domain, namely *ImAxes* by Cordeil et al. [4] and *Ground Control* by Katins et al [14].

The two applications visualize the same underlying DAW, which is the widely used and extensively documented *rnaseq* workflow. This workflow, written in the Nextflow system, is designed for the processing and analysis of RNA sequencing data. It is a representative example of real-world DAWs, comprising interconnected processing nodes, diverse data paths, and distinct input/output nodes. Figure 2b shows a workflow diagram of *rnaseq*. Rather than supporting the import or selection of custom workflows, we opted to limit the experience to this single, well-documented example for easier comparison.

The two prototypes differ in their interaction and visualization strategies, particularly in how users navigate, inspect, and interpret the workflow structure. By presenting two contrasting immersive experiences, we aimed to gather varied responses and critical reflections from participants. Both prototypes were deployed on the Meta Quest 3[3] headset.

For the remainder of this section, we refer to the two prototypes as **DAW Grabber** and **DAW Walker**, respectively. Each is described in more detail in the following two subsections.

3.1.1 Prototype 1: DAW Grabber. Participants viewed the DAW anchored in their surrounding physical environment using the AR passthrough functionality of the Meta Quest 3. This prototype was influenced by the *ImAxes* [4] prototype, which demonstrated how data visualizations can become more intuitive and engaging when users are able to directly grab, move, and manipulate visual elements in space.

Figure 3a and Figure 3b show exemplary views of this prototype. Instead of using controllers, participants interacted through freehand gestures, including grabbing nodes, pinching to press buttons, and performing a right-hand pinch with the palm facing inward to open a menu. After a short tutorial, the workflow appeared as a 3D visualization of five interconnected stages. Each stage was a movable, labeled rectangle with an interactive button for revealing details. Inside the stages, nodes were visualized as colored cards, green for applications, blue for data I/O, and red for inter-stage links. At any time, users could rearrange stages and nodes spatially to inspect and interpret connections. The menu button returned the user to the overall stage overview for navigation.

3.1.2 Prototype 2: DAW Walker. The second prototype was developed in Virtual Reality (VR) to explore immersive interaction

[3]https://www.meta.com/de/en/quest/quest-3, last accessed on 2026-01-16.
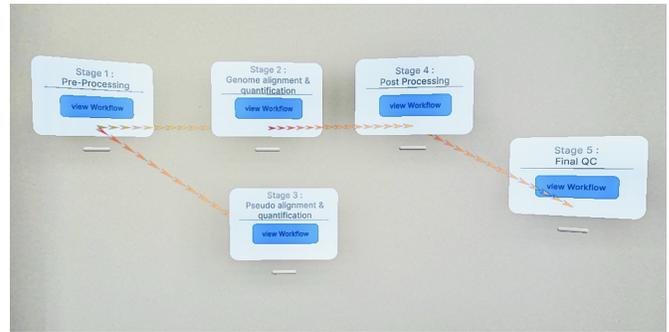
(a) Initial view of the DAW Grabber prototype. The five main stages of the *rnaseq* workflow are displayed as movable panels within the user's physical space. Each stage can be freely repositioned and expanded for closer inspection of its internal nodes.

(b) Stage 1 of the *rnaseq* workflow opened for inspection. All processing steps within the stage are visible, including associated input and output flows.

Figure 3: Interaction with the DAW Grabber prototype. Users can spatially explore and manipulate the *rnaseq* workflow by repositioning and inspecting its stages and respective internal steps in nested views using gestures.

without the physical constraints of the user's environment. Unlike the first prototype, which anchored the workflow in the user's room, this VR prototype enabled participants to enter and navigate a fully spatialized version of the DAW. This design was inspired by the *Ground Control* [14] prototype, which introduced the idea of walking on data visualizations to strengthen embodied engagement and spatial comprehension.

In this prototype, nodes were represented as elevated platforms arranged across a virtual environment, allowing users to physically walk between them. Each platform displayed an information screen that appeared when stepped on, providing context such as the application stage, its function, and the associated data flow. Input and output nodes were color-coded, and directional arrows indicated the flow of data through the workflow. The *rnaseq* workflow's stages were laid out to reflect their logical sequence, allowing users to literally "walk through" the analysis process. Figure 4a and Figure 4b show how one user was able to see the DAW in front of them.

This prototype emphasized the idea of embodied navigation. By using walking as the primary interaction modality and a spatial
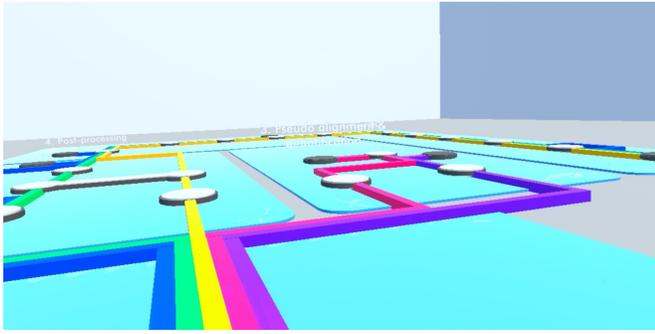
(a) User perspective from the end of stage 1 in the *rnaseq* workflow. The view faces "east", looking ahead toward the subsequent stages 2 to 5 positioned in front.
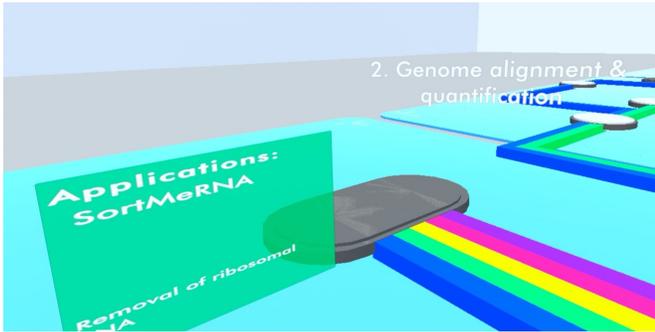
(b) Close-up view of an output node in stage 1 of the *rnaseq* workflow. Additional textboxes provide detailed information about the node's function and its role in the data flow.

Figure 4: Interaction with the DAW Walker prototype. This prototype brings the workflow diagram shown in Figure 2b into an immersive virtual environment, allowing users to walk through and inspect the *rnaseq* workflow spatially. Nodes are represented as interactive platforms with contextual information, enabling embodied exploration of the DAW.

layout on the ground, we aimed to show the participants another way in which IA could potentially be used to interact with DAWs.

3.2 Participants

Participants were recruited through word of mouth and relevant academic mailing lists, with the goal of attracting individuals of varying levels of expertise who were nonetheless likely to engage with DAWs during their careers. A total of 18 volunteers agreed to take part in the study. Their ages ranged from 19 to 55 years ($\bar{x} = 27$, $s = 8$). Among them, 15 were students, including five PhD candidates. Most of them had a background in natural sciences, a domain where the use of DAWs is common. The remaining participants included a project assistant, a secretary, and a research associate. Eleven participants identified as male, while seven participants identified as female. In terms of domain-related experience, seven participants reported regularly working with DAWs. 17 participants reported having used XR technologies before. Of these, 15 had used a VR headset before, though only four reported using one regularly,

averaging up to three hours per week. Participation in the study was entirely voluntary, and they were free to withdraw at any time.

3.3 Procedure

Once the participant was present, the session began with a welcome and a short introduction to the study. The participant was then given an informed consent form and study instructions. Before using the IA prototypes, participants were briefed on how to operate the headset, including its controls and gesture-based interactions. The order of prototypes followed a balanced Latin square to avoid learning effects.

To ensure participants engaged with all aspects of the IA experiences, they were asked to complete a set of exploratory tasks during the session. These tasks were designed to guide interaction with different features of the applications, but they were not graded or assessed in any way. Depending on the prototype, tasks included listing the names of stages, counting the number of nodes in specific stages, identifying input/output nodes, recognizing file types, or analyzing how nodes and stages were interconnected. Throughout, participants were encouraged to think aloud, verbalizing their thoughts and impressions while navigating and interacting with the applications.

After each application session, participants completed a short survey consisting of open-ended questions, inquiring about their overall impressions, perceived usefulness, memorable aspects of the experience, and any suggestions for improvement. The overall study took around one hour on average.

3.4 Data Analysis

To analyze the collected qualitative data, two researchers independently coded all participant responses. The coding process followed the *Gioia Methodology* [10], a structured qualitative approach that helps inductive concept development while remaining grounded in participants' own terms and expressions.

Initially, first-order codes were extracted directly from participant language to preserve their perspectives as closely as possible. These were then collaboratively grouped into second-order themes that captured more abstract interpretations and theoretical patterns. Finally, these themes were organized into overarching aggregate dimensions that reflected the broader implications of the data. This method was chosen for its systematic, yet still flexible framework, helping us with the exploratory research goals of this work.

At the same time, we acknowledge limitations in applying the Gioia methodology to the qualitative data collected in this study. Gioia analysis is commonly used with richer data sources, such as in-depth interviews, whereas our data primarily consists of open-ended questionnaire responses that provide less contextual depth. Consequently, the resulting themes should be interpreted as exploratory and descriptive rather than as a basis for developing new conceptual models. We nonetheless chose the Gioia framework over lighter-weight approaches (e.g., thematic analysis) because it offers a transparent and systematic structure for organizing participant-driven insights, which was well-suited to the exploratory goals and comparative nature of this work.

4 Results

The analysis of participants' responses revealed four key themes that characterize their experiences and perspectives on using the two IA prototypes for interacting with DAWs. Following the aforementioned qualitative coding process, we identified a set of first-order concepts and second-order themes, which were grouped into the following four emerging aggregate dimensions: **Immersion and Embodiment**, **Visualization and Comprehension**, **Usability and Interaction Design**, and **Engagement and Communication**.

4.1 Immersion and Embodiment: Enhancing Engagement through Physical and Spatial Interaction

Participants described the immersive and embodied qualities of the prototypes as a key contributor to their engagement with the workflows. The combination of physical movement and spatial interaction fostered a strong sense of presence, making the exploration process feel both intuitive and rewarding:

> *"It felt more like I'm actually progressing along, which I don't experience when I'm looking at a 2D representation."* (P02, DAW Walker)

Users mostly appreciated how movement through the workflow reinforced a sense of progress and allowed for more natural interaction with complex structures, but not all were in agreement on this:

> *"Because I felt like I'm physically moving through the stages, it felt more like I was accomplishing big steps rather than if I just had a diagram."* (P06, DAW Walker)

> *"Unproductive to walk from node to node instead of seeing them all grouped in once."* (P03, DAW Walker)

The spatial arrangement of workflow elements, enhanced by visual features such as specific coloring and its layout, supported spatial reasoning, helping participants better understand scale and complexity. Locomotion techniques like flying or teleporting were seen as potentially useful for navigating larger workflows in the future. Overall, the interaction style was experienced as positively engaging and even game-like, suggesting that embodiment in immersive environments can enhance both usability and user motivation when working with (scientific) workflows.

4.2 Visualization and Comprehension: Supporting Understanding of Complex Workflows

Participants highlighted the strength of the prototypes in facilitating comprehension of complex workflows through their dynamic and interactive visualizations. The system's stepwise walkthrough and immersive visualization style supported both learning and inquiry, especially for unfamiliar or rather complex workflows:

> *"Large workflows where one application flows into several more could be represented very well."* (P02, DAW Grabber)

> *"This would be also great to visualise branching workflows."* (P07, DAW Walker)

The 3D layout and spatial positioning of elements enabled users to maintain a clear sense of orientation and gain informative overviews. Features such as nested representations were praised for revealing additional structural depth and contextual detail, offering more than what traditional static diagrams typically convey:

> *"I feel like [this XR] application would benefit very complex workflows where a 2D visualization would require line/path crossings. In 3D this could be visible more easily."* (P09, DAW Walker)

However, many participants also reported feeling overwhelmed by the sheer amount of visual and structural information presented at once. The immersive environment, while powerful, seemed to introduce a high cognitive load during use. While the prototypes were generally seen as helpful, some participants expressed concerns about their scalability, suggesting that their benefits might diminish with increasingly large or complex workflows. Participants were split about whether the IA prototypes would actually reduce or increase the feeling of being overwhelmed:

> *"To replace very complicated workflows that have a lot of steps and branches, this way of visualizing is a lot clearer and less overwhelming (because not everything is squeezed onto the screen all at once, and you "physically move" through the steps)."* (P06, DAW Walker)

> *"Definitely for shorter workflows, though. Otherwise, [it would be] too overwhelming."* (P05, DAW Grabber)

Suggestions for improving overview mechanisms, such as maps, the possibility to zoom, or progress indicators, point to the value of more perspectives and Quality-of-Life features in aiding comprehension.

4.3 Usability and Interaction Design: Intuitive Interaction, But Known Device-Specific Drawbacks

Participants generally found the prototypes intuitive and easy to use, highlighting the simplicity of movement and direct manipulation as positive aspects of the interaction design:

> *"I was surprised by how easy it was to move around the workflow components"* (P12, DAW Grabber)

The system was described as responsive and robust, with actions like "working with hands" (P14) and moving around the environment contributing to a mostly satisfying user experience. However, several usability and design issues emerged, particularly around navigation and orientation. Users noted that navigating large workflows could be distracting or disorienting, and the homogeneous appearance of nodes made it harder to distinguish between elements:

> *"It was easy to get disoriented because the nodes all look the same [...], that makes it sometimes difficult to grasp which direction one is facing."* (P11, DAW Walker)

Some interface aspects, such as the mechanism for exiting nested views or interpreting directional arrows, were found unintuitive. Additionally, physical discomfort and system limitations, including headset fatigue and motion sickness, occasionally disrupted the experience. One participant summarized this as follows:

1st Order Concepts

2nd Order Themes

Aggregate Dimensions

- Physical movement increases immersion
- Immersive interaction is fun and intuitive
- Feeling of progressing through the workflow

→ Immersiveness and Presence

- Spatial structure helps to grasp a sense of scale
- Structure and color help to visualize complex workflows

→ Spatial Reasoning Support

- Moving through the workflow feels rewarding and like progress
- Grabbing elements for better analysis helps understanding

→ Physical Movement

- Flying and teleporting to far-away nodes might be helpful

→ Locomotion

- Positively interactive and game-like, engaging to play around
- Engaging point of view

→ Engaging Interaction

Immersion and Embodiment

- Helps with understanding (complex) workflows
- Stepwise walkthrough helps understand the whole workflow
- Great for learning and inquiring about new workflows

→ Workflow Comprehension

- Informative visualization; enables a good overview
- Easy to understand the current position in the workflow
- 3D layout offers a lot of new possibilities, helpful for finding new visualizations (also 2D) in general

→ Visualization Effectiveness

- Entering nested modules is interesting, it helps understand nested structures better
- Gives more information per node than with a static diagram

→ Nested Representation

- A top view (birds-eye view), zooming, a map, and/or a progress bar might be helpful

→ Overview and Points of View

- Too much information at once, overwhelming experience

→ Cognitive Load

- Not ideal for huge workflows, yet still helpful for these as well
- Better understanding of each step and its connections

→ Scalability

Visualization and Comprehension

- Easy to use and move around, intuitive controls easy to learn

→ Usability

- Navigation is distracting from the actual information
- Easy to lose orientation in large workflows, homogeneous node design needs refinement

→ Navigation and Orientation

- The system seemed robust, interaction went well
- "Working with hands" was nice, moving around felt good

→ Feedback and Responsiveness

- Headset annoying to wear and distracting, motion sickness
- Limited overview due to position in 3D

→ System Limitations

- Input/output nodes and arrows are confusing
- Button to go back from nested view is unintuitive

→ Usability Breakdowns

Usability and Interaction Design

- Great to present workflows, could replace whiteboards
- Good for both personal use and presentations

→ Presentation and Demonstration

- Helpful for collaborative work and remote teams
- Helpful to show layperson workflow

→ Collaboration and Sharing

- Engaging to play around with nodes, but still relatively primitive in use and features
- Good compromise between overview and details

→ Playfulness and Engagement

- Helps to understand the detailed steps of a workflow in general
- Great to learn about workflow in early stages

→ Educational Use and Learning Potential

- Could be used beyond DAWs
- Interesting for personal use, helps with keepingan overview of processes in general

→ Personal Use Cases
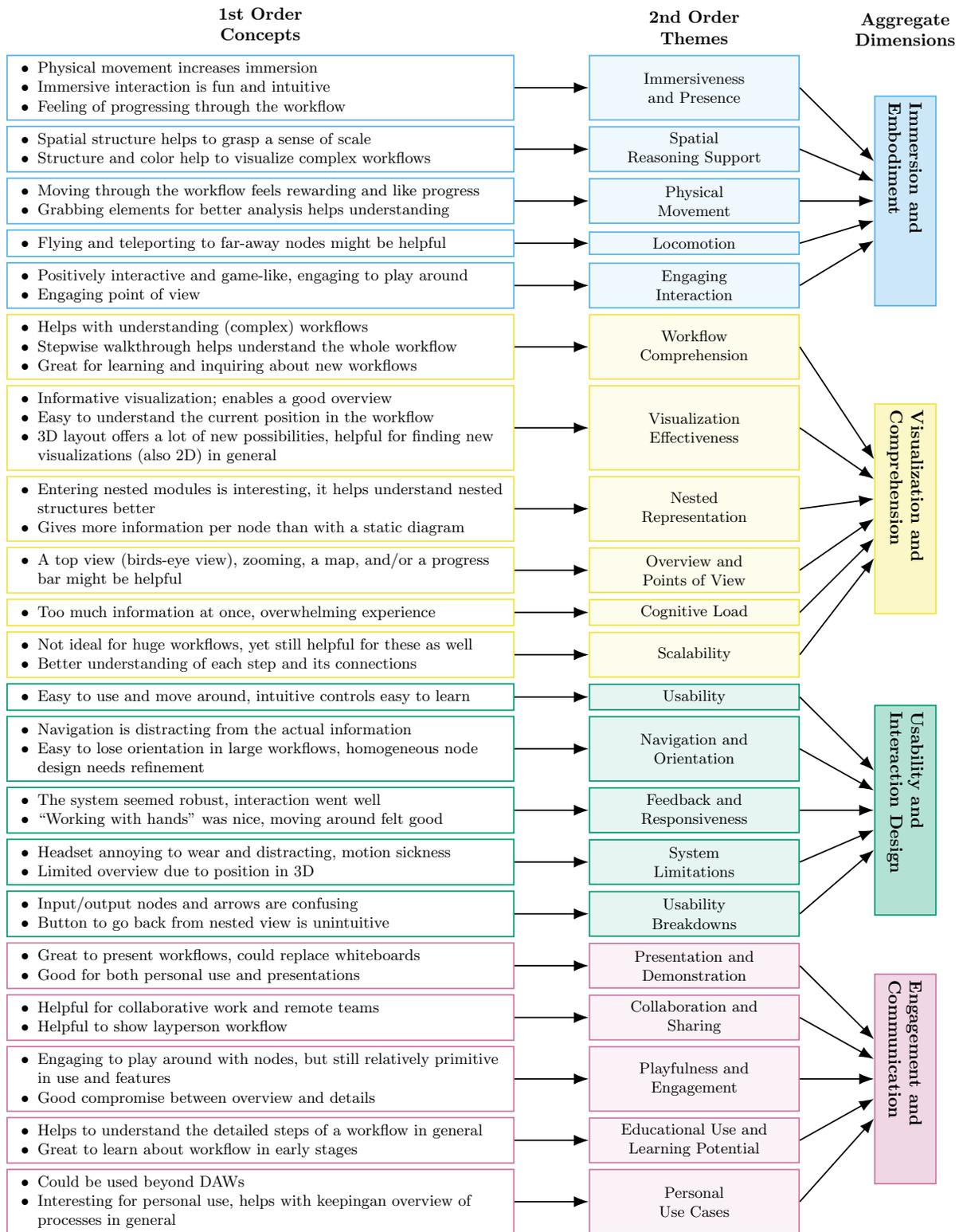
Engagement and Communication

Figure 5: Structure of qualitative findings following the Gioia methodology. The diagram illustrates the data structure from first-order concepts to second-order themes and the final four emerging aggregate dimensions related to IA use for DAWs.

"The main issue was the limitation of the device, i.e., the hand tracking accuracy and resolution of the camera and display, and the weight of the headset. I could see myself using a similar software with a more advanced device." (P09, DAW Grabber)

4.4 Engagement and Communication: Exploring Use Cases Beyond Analysis

Participants identified strong potential for the prototypes beyond individual analysis, emphasizing their value for presentation, collaboration, and educational contexts. The system was considered particularly effective for demonstrating workflows to others, offering an engaging alternative to traditional tools like whiteboards, and was seen as useful both for personal understanding and external communication. Participants envisioned applications in collaborative settings, including remote teamwork and explaining processes to lay audiences:

"This seems really useful for groups [...], as you can collaboratively set up a workflow and discuss it as you go." (P12, DAW Grabber)

"[...], this would be a great tool to visualize and present one's work on a fully established workflow, and I can even imagine using it to run a short and simple workflow example with test datasets for demonstration purposes, which would be a really innovative way to present people [...] my workflow." (P01, DAW Walker)

The playful and exploratory interaction style contributed to engagement, although some users noted that the system still felt somewhat primitive in terms of functionality:

"I think this application allows for a better basic understanding, but may be limited in terms of complex work on the workflow." (P16, DAW Grabber)

Importantly, the immersive interactive environments were recognized as a valuable learning tool, particularly for breaking down complex workflows into understandable steps. Several participants also suggested personal use cases outside of DAWs, highlighting the systems' general potential for supporting process-oriented thinking.

5 Discussion

Our findings offer insights into the broader design space of IA environments for DAWs. Participants described embodied interactions, such as physically moving through data structures or manipulating workflow elements "by hand," as contributing to their experience of engagement and presence. The spatial affordances of these XR prototypes were seen as beneficial for building mental models of complex processes, especially when combined with interactive features like nested views or the possibility of literally walking through a workflow. **These forms of interaction appear to help intuitive understanding and encourage users to explore and reflect on DAWs in new ways.**

IA environments like **DAW Walker** could be particularly effective for engaging newcomers, supporting onboarding, and motivating exploration by making workflows tangible and approachable. IA environments like **DAW Grabber**, on the other hand, may be better suited to more complex workflows by offering greater spatial flexibility, though it, too, is subject to scalability limits that warrant further investigation.

At the same time, the findings point to key challenges that must be addressed for IA tools for DAWs to scale effectively. Many participants reported a high cognitive load, even when faced with the, in comparison, only moderately complex *rnaseq* workflow. With larger or more information-dense workflows, it seems only logical that these kinds of IA environments can quickly become overwhelming without adequate structuring or abstraction. The mentioned visual complexity, limited overview mechanisms, and navigational issues likely contributed to this sense of overload. **To support comprehension without disorientation, future immersive systems should incorporate techniques such as progressive disclosure, adaptable points of view, and lightweight overview tools like minimaps or progression bars.**

Several limitations mentioned by participants reflect the current state of XR hardware rather than software design: headset discomfort, motion sickness, and restricted fields of view are well-documented issues with today's devices. These constraints should be considered when designing immersive analytics tools, but they are likely to diminish as the technology matures. In the same vein, interaction design remains crucial. While many participants found the XR interfaces easy to use and learn, others encountered confusion, particularly around navigation, orientation, and the clarity of interface elements.

Beyond technical considerations, the study highlights the communicative and educational potential of IA environments for DAWs. Participants saw value in using the XR prototypes for presentations, collaborative analysis, and onboarding laypeople. The engaging, often playful nature of immersive exploration was noted as a strength, even when the tools were still in an early stage of development. As domain scientists who rely on DAWs are not necessarily trained in computer science, IA environments have strong potential to help them grasp the essential concepts and work effectively with the DAWs they use, without requiring them to learn relatively complex or out-of-scope material. **Consequently, future research should not focus solely on interaction with DAWs as systems in use or under development, but also examine how IA environments could be used to teach underlying concepts and to communicate the functionality of a DAW that is relevant to domain scientists.**

Our results can also be situated within recent work exploring alternative interaction paradigms for working with DAWs. For example, prior research has investigated the use of conversational interfaces such as large language models to support DAW development and modification [22]. While such approaches lower entry barriers by abstracting technical complexity through natural language, they primarily operate on symbolic or textual representations of workflows. In contrast, our findings suggest that moving beyond increasingly complex two-dimensional visualizations toward immersive, spatial representations can support understanding and engagement among users with diverse levels of technical expertise. In this sense, IA-based approaches complement conversational tools by offering another way to convey workflow structure and execution logic. This aligns with previous work highlighting how

direct manipulation and embodied interaction can foster agency, engagement, and exploratory behavior in interactive systems [4, 14], suggesting that natural interaction modalities may be particularly valuable in complex analytical contexts.

The results further suggest that while IA environments can enhance engagement and provide novel perspectives on workflow structure, there appears to be a threshold of workflow size and complexity beyond which such representations risk becoming convoluted rather than helpful. This challenge was particularly evident with **DAW Walker**, where users were unable to perceive the entire workflow at once and instead had to physically navigate through it, potentially hindering "global" understanding. **DAW Grabber**, by contrast, points toward how employing the third dimension and a wider spatial field, potentially through 360-degree or roomscale displays rather than traditional 2D screens, might alleviate some of these limitations. However, further research is needed to better understand where additional display real estate and spatialization meaningfully support comprehension, and where increasing immersion begins to break down due to cognitive or perceptual overload.

In summary, IA seems to offer promising opportunities for enhancing how users engage with, understand, and communicate about DAWs. However, realizing this potential requires addressing the quickly overwhelming nature of IA, refining interaction design, and anticipating the constraints of current and near-future XR technologies.

6 Conclusion

This work set out to explore how IA could potentially be used to help improve user comprehension, usability, and engagement when interacting with DAWs, which are often highly complex and difficult to interpret through code or static diagrams alone. Motivated by the potential of IA to address these challenges, we developed and evaluated two XR-based prototypes through a within-subject study. Our findings suggest that IA environments hold considerable promise for supporting users as they work with large-scale data analysis workflows. The ability to visualize these in more intuitive spatial layouts, using embodied interaction and more engaging presentation formats, makes IA a compelling approach for visualizing and interacting with DAWs. At the same time, the study surfaced several limitations. Participants highlighted issues related to scalability and cognitive load, especially in large or information-dense workflows. Furthermore, while interaction was generally perceived as intuitive, several users encountered navigation difficulties and expressed a desire for greater control in how information was presented and a reduction in the initial information given to reduce being overwhelmed by it. As immersive technologies continue to evolve, future research should explore more refined interaction paradigms, support for collaborative usage, and integration with real-world analysis tools. By building on these foundations, IA has the potential to make complex data workflows more transparent and accessible, especially for domain experts who may not have extensive software engineering knowledge, thereby supporting more effective engagement with their analysis processes.

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