Visualization Viewpoints

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Data Visualization on Interactive Surfaces: A Research Agenda

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Interactive tabletops and surfaces (ITSs) provide new opportunities for the analysis and communication of data using visualizations. Their potential to transcend the possibilities of desktop screen-, mouse-, and keyboard-based systems are making them increasingly attractive. Touch devices, for example, promise to be easier or more comfortable to use and are often thought to be more intuitive. Also, touch interaction can outperform mouse input for target selection,[1] foster awareness in collaborative settings,[2] and provide important somesthetic feedback.[3] ("Somesthetic" refers to bodily sensations.)

As visualization practitioners, we should therefore embrace and explore the possibilities that ITSs offer.[4,5] Yet, as ITSs slowly become part of our everyday environment, we still have numerous open research questions at the intersection of visualization and ITSs. To explore this research space, we held the 2011 Workshop on Data Exploration on Interactive Surfaces (Dexis 2011; www.aviz.fr/dexis2011). Here, we discuss this research space and present the research agenda for information visualization, scientific visualization, and visual analytics on ITSs that emerged at the workshop.

ITSs' Value for Visualization

Despite the increasingly common use of ITSs, we don't yet fully leverage their possible benefits for visualization. For example, interactive surfaces offer alternative and potentially more effective and engaging ways to use visualizations, making data more accessible and insight formation more attainable. So, novel visualization systems for public, collaborative, and mobile settings can promote visualization use to a broad range of users beyond the traditional audience of data analysis experts.

ITSs also increasingly come in the form of larger screens (for example, wall-sized displays), potentially with much higher pixel counts than desktop displays. These high-resolution displays can display large amounts of information at a glance and provide space for sensemaking and collaborative analysis. Both the higher pixel count and the leveraging of the data analysis capabilities of multiple people can help to deal with the increasing data complexity. This could in turn lead to a better user experience and more satisfying use of visualizations for reading, learning from, communicating, or analyzing data.[6]

The Challenges and the Research Agenda

To learn how to best leverage the possibilities of ITSs for visualization, researchers must address three main types of challenges. The first is the technical challenges of understanding, using, and

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effectively combining novel displays and their interaction capabilities. The second is the design challenges related to data representations and interactions with them for ITS. The third is the social challenges of using visualization applications in novel contexts such as museums, meeting rooms, or other nonwork settings.

The Technical Challenges

These challenges concern the role of the environment in which visualizations will be used. We discuss them according to the surface types and combinations of ITSs.

Surface types. Different types of interactive surfaces have different types of affordances. These affordances can make a particular surface more amenable to certain types of visualization. For example, shared work or presentation tasks are often considered the appropriate domain of large upright displays, whereas independent activities or control tasks can be relegated to horizontal surfaces and laptops.[7]

Moreover, a surface type's physical location influences its use in social visualization settings. A large display in a hallway might best support more casual visualization settings—for example, to provide an ambient display or support an ad hoc discussion between colleagues. The same display in a meeting room might be most useful for dedicated, planned use of visualizations—for example, for collaborative data analysis.[8] These technical factors and their influence on the appropriateness of surfaces for visualization tasks require further investigation.

In addition, the surface type influences which types of visualizations might or might not be suitable. The screen real estate also influences how much data a visualization can show. For example, wall-sized displays can show large, detailed overviews, whereas personal devices can display only rough overviews or small detail sections.[6]

The sidebar "Visualization in an Exhibition Context" describes a case in which the developers had to decide both which surface type would best support data exploration and what type of visualizations and interactions to provide. The surface had to catch the audience's attention and be easily approachable, shareable, and large enough to hold geospatial data in a resolution that affords exploration. The developers built dedicated lens-based access to the data to allow the types of exploration common in this context. This example illustrates that, in general, we need to investigate what types of surfaces and surface settings are best suited for what types of visualizations, visualization tasks, represented data, representations, and interactions.

Combining ITSs. Multidisplay environments (MDEs) are typically prototyped in dedicated workrooms. They often contain different types of interactive surfaces such as whiteboards and tabletop displays, and might contain infrastructure integrating multiple mobile devices (for example, tablets, laptops, and handhelds).

Interactive tabletops and surfaces (ITSs) provide new opportunities for the analysis and communication of data using visualizations.

MDEs present exciting opportunities for visualization:

- They provide a larger, discretized display space for analysis, so users can visualize more data at a given time.
- They can semantically separate data across different devices.
- They allow the distribution of visualization tasks across individuals so that they can work independently when required.

They also present some interesting questions:

- What roles do visualizations play on different displays (and surfaces)?
- How should we conceptualize the relationships between the visualizations?
- How can work with the visualized data be coordinated in these spaces?
- How do visualizations designed for different screen scales work together?

As we just discussed, certain types of analytic tasks might lend themselves to specific form factors. For example, in an MDE, presentation and sharing could occur on a large display, and detailed exploratory investigations could occur on personal displays. However, when work is distributed across displays in which some actions are more visible than others, coordinating the activity becomes a challenge. Evidence suggests that using a subset of these displays for overviews of people's activities can aid coordination.[9] This again suggests both an alternative conceptualization of displays' role in

Visualization in an Exhibition Context

Exhibitions—particularly those in science centers—often must present large datasets in compelling, easily understandable ways. Visitors spend only a few minutes with each exhibit and will quickly abandon exhibits they don't understand. This brief moment of attention contrasts with the large amount and complexity of available data, often full of hidden relationships.

One such exhibit was GlobalData (see Figure A), an interactive tabletop that was part of Science Express Germany, an exhibition train that traveled through Germany in 2009.[1] The context of a data exhibit presented many of the challenges discussed in the agenda described in the main article: which surface type to choose, what representations to display, which interactions to provide, and how to support collaboration.

GlobalData focused on human-induced changes to the Earth. The data pool comprised 50 pages of a National Geographic special edition, including many

Figure A. Visitors interacting with GlobalData, a tabletop display that focused on human-induced changes to the earth. (Source: Archimedes Exhibitions; used with permission.)

MDEs and that these spaces might require additional data visualizations. Rather than simply depicting data for task-centric purposes, visualizations might need to display "metatasks" to support group work.[2]

A principal question is how to manage and move information across displays. This raises issues of ownership and control (who can manipulate content, and where can they manipulate it?) as well as different mechanisms for data transfer and replication. For example, when different displays show the same data, should only changes to the view of this data be allowed, or are changes to the underlying data itself possible? If the latter is the case, how do we visually propagate data changes to all the displays?

In short, visualizations for MDEs must not only be effective and successful for a single surface but also work well and integrate with visualizations on other surfaces. MDEs thus pose not only coordination challenges but also the other challenges we discuss in this article.

The Design Challenges

Here, we highlight the challenges of

- data representations for ITSs,
- touch interaction as a popular type of ITS input, and
- effectively coordinating input and data dimensions.

For additional input-related challenges, see "Beyond Mouse and Keyboard: Expanding Design Considerations for Information Visualization Interactions."[5]

maps and statistics, and supplemental images and videos. Ulrich von Zadow and his colleagues built the exhibit around several maps of the earth, displaying different data overlays such as population density and overfishing.

Data exploration tools called GeoLenses let several people concurrently explore the large amount of data presented.[2] Users simply tapped the table to open these circular lenses to show map overlays; they used dragging motions to move the lenses. Menus, sliders, and buttons around the lenses let users switch the data overlay, change parameters, or display additional data. For example, in the population density view, users employed a slider to change the year displayed (see Figure B).

Observations of visitors showed that the design and technical setup supported and encouraged widespread collaboration (see the section "Collaboration" in the main article). Often, users opened lenses and shared interesting views, something that noninteractive displays wouldn't have allowed. It also became clear that it's essential to keep the interaction as simple as possible in this context. About a third of the visitors interacted with only one finger, and many of those never used dragging gestures. Nevertheless, the exhibit allowed even these people to fully access the application's functionality.

Implementing the exhibit also involved the challenge of adequate software support for a touch-based visualization application. Von Zadow and his colleagues used libavg (www.libavg.de), an in-house media development toolkit. Libavg provided the necessary higher-level graphics capabilities (for example, vector graphics, formatted text, interactive masking of subscenes, and videos). However, because it delivered only low-level multitouch events, they spent much time coding interaction basics.

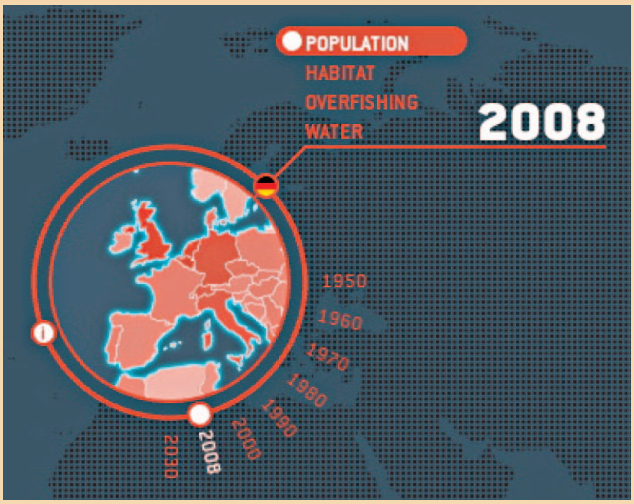

Figure B. A GeoLens showing Europe's population density in 2008. Users simply tapped the table to open these circular lenses to show map overlays; they used dragging motions to move the lenses. (Source: Archimedes Exhibitions; used with permission.)

Partly because of this experience, they expanded libavg to support a variety of touch interaction techniques.

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Data representations. Guidelines exist for developing visual representations for standard desktop displays—for example, regarding which types of data encoding are most useful for depicting certain types of data. But are these guidelines applicable to other surfaces? A recent study showed, for instance, that the distortion due to extreme viewing angles on very large displays introduces additional errors in the correct perception of angles or areas.[10] The perception of the color of small data elements can also be negatively affected, particularly on tiny displays in outdoor viewing conditions.[11]

So, we need to conduct more studies to understand how surface types and viewing conditions affect our perception of visualizations. Clear surface-specific guidelines, perhaps bundled in visualization toolkits, will help us develop visualization applications and, consequently, increase the audience that benefits from visualization use.

Touch interaction techniques. Compared to the traditional mouse interactions that support a simple point-and-click mechanism, multitouch interactions give people additional degrees of freedom to express their intentions and provide more direct access to their objects of interest. Touch interaction can be realized in many ways; however, not much research has investigated how people can best use it for visualizations. As a first step, researchers have observed how people naturally interact with charts in a multitouch setting.[12] The results give an initial indication of the many ways people can use hands and fingers to manipulate data.

A systematic vocabulary of touch interactions for visualization would also be useful. (Efforts are

underway to develop a vocabulary for human-computer interaction—see, for instance, www.gispl.org.) Such a vocabulary could further enable people to interact with different visualization systems without having to learn interactions specific to a particular system. In other words, a unified vocabulary will reduce the load of learning touch interactions and improve touch interaction literacy. Bundling such a vocabulary into visualization toolkits that natively support multiple points and types of input could greatly assist developers in making visualization systems for touch-enabled ITSs.

ITSs must facilitate the modification of multidimensional data through the coordination of input from 2D touch points.

This vocabulary's development involves two main considerations. First, because the data type is often related to the specific task, different data types or representations call for different interactions. However, a particular gestural interaction could—depending on the visualization—cause different changes to a view, a representation, or the underlying data. For example, a touch-and-drag interaction might mean a move for a 2D chart but a translation or rotation around a specific axis for a 3D flow visualization.

Second, it would be useful for touch interactions to support different levels of complexity or power to cover tasks for a wide audience. For example, laypeople should be able to perform more casual data exploration without learning complex gestural interactions.

The difficulty of developing a vocabulary also greatly affects the difficulty of enriching visualization toolkits with dedicated multitouch interaction capabilities.

Data and interaction dimensionality. The touch input that's predominantly used for controlling ITSs is always captured on a 2D surface, whereas the data to be explored is often defined in a higher-dimensional space. This is a challenge unique to ITSs because desktop applications, in contrast, provide interactions with such higher-dimensional spaces through

- different modalities via mouse or keyboard buttons,
- a set of dedicated widgets (sliders, drop-down boxes, arcballs, and so on) with mouse or mouse-plus-keyboard input, or even
- dedicated input devices.

However, ITS users typically can't or won't exploit these techniques. Changing modalities through physical buttons is impossible because there are no buttons. Widgets don't always make sense for ITSs (for example, given the orientation problem on tabletops) or simply don't fit the available interaction surface (for example, on mobile devices). And users often don't want dedicated devices because they expect ITSs to employ touch-only input.

So, ITSs must facilitate the modification of multidimensional data through the coordination of input from 2D touch points. For visualizing high-dimensional abstract data, this restriction is usually no problem. Many data representations—for example, parallel coordinates—aim for a visual mapping from the data space to the image plane. So, the 2D interaction paradigm nicely fits the 2D visual representations. Similarly, data that's inherently 2D (for example, map-based data) can be interacted with relatively easily.

This problem remains, however, for data that's defined and explored in a 3D spatial domain (for example, medical scans and physical simulations). When using direct touch as the primary interaction metaphor for such visualizations, we need to find intuitive mappings from the 2D input space to the 3D data domain. This is an important issue owing to the directness and perceived "naturalness" of touch input. People seem to base their interaction with ITSs on their everyday interaction with real-world objects.

Moreover, users must be able to navigate in the 3D data space regardless of the data type (for example, volumetric versus isosurface versus particle data). This means we must solve other problems besides how to map 2D touch input to 3D manipulation. Many general mouse- or touch-based 3D interaction techniques aren't directly applicable. Most of them require individual objects of at least a certain size in the dataset to constrain the 3D interaction on the basis of the input configuration. Such meaningfully accessible objects don't exist, for example, for particle clouds or volumetric datasets.

The problem gets more complicated for stereoscopic displays that can detect touch input.[13] Here, we must also decide where to display the 3D data with respect to the 2D touch surface. Placing 3D data elements far from the surface leads to numerous problems including parallax issues, people "bumping into" the invisible touch surface, and

people having to "touch through" objects they see. On the other hand, the touch surface can't always be close to the focus locations in a 3D dataset; this challenge requires further research.

For examples of applications that deal with some of these challenges, see the sidebar "Touch-Based Exploration of Visualizations of Spatial 3D Data."

The Social Challenges

These challenges include issues of collaboration and evaluation.

Collaboration. On large multitouch displays, several people can interact simultaneously, whereas smaller devices can transmit and receive information quickly and effortlessly from collaborators in distributed locations. We need to understand how to best support social exchanges when people gather to look at or distribute visualizations and how to support them as they switch from working individually to working collaboratively.

So, it's important to examine how best to merge people's visualizations and present them for collaborative use. Features that promote awareness of what others have looked at, analyzed, created, or discussed could also help small and large groups synthesize their analysis results.[2] Step-by-step instructions could further improve how people transition between working individually and collaboratively.

Moreover, we don't know which types of visualization tasks and data representations work best in collaboration. Do some representations support groups better than others? What visualization tasks or interactions might people prefer to do alone? Also, we don't yet have clear guidelines for using visualizations in time-critical, intense, data-driven scenarios such as emergency response or mission control.

Before we can understand the social implications of visualization on ITSs, we'll need to explore many types of data, visualizations, and social groups.

Evaluation. To better understand how ITSs can support visualization-based data analysis (especially in collaborative settings), we must conduct dedicated evaluations. The question of how to evaluate a visualization's success is difficult. It becomes even more difficult if we want to tease out an interactive surface's role in a visualization tool's efficiency and effectiveness, or a user's satisfaction with that tool. As with visualization in general, this higher-level question might not be easily answered in one session; it will likely require many long-term assessments and perhaps dedicated study methodologies.

This last point is particularly crucial. Visualizations on ITSs typically don't comprise just a single, easily controllable visualization that we compare to a second visualization with respect to time and error. Instead, we'll typically face complex visualization environments with complex interaction techniques operated, potentially, by several people simultaneously. We probably won't be able to easily evaluate these scenarios on the basis of time and error. Instead, we want to understand how to improve ITS visualization settings to better support data analysis.

On a lower level, we also must understand how representations or dedicated novel interaction techniques affect data analysis. For instance, we don't yet truly understand how touching virtual data affects comprehension or memorability of information. We hope to see more dedicated user studies conducted at the intersection of ITSs and visualization to help us understand and communicate the value ITSs add to data analysis.

Many factors influence successful data analysis on ITSs. So, more dialogue is necessary between researchers in visualization, human-computer interaction, computer-supported cooperative work, and other related fields. Such dialogue will help to more strongly communicate ITSs' value to the visualization community.

We also need to develop and deploy systems that clearly demonstrate ITSs' value and benefits. To support such development, we must offer a clear, structured design space. Currently, too little effort is invested in creating guidelines, heuristics, and best practices for ITS visualization. Also, too few toolkits and software frameworks support developers in efficiently engineering ITS visualization interfaces. So, we must focus attention on these issues, evaluating whether we can establish generalizable guidelines, reusable practices, and software frameworks that support the efficient engineering of appropriate, powerful, and appealing visualization platforms on ITSs.

A few success stories exist, particularly in museums and command-and-control centers, but we need more alternative deployments and reports or evaluations of their use. Because visualization research is just beginning to embrace the possibilities of novel display devices, it's perhaps unsurprising that few systems exist whose success has been widely communicated. The Dexis proceedings briefly introduce the variety of applications and challenges that researchers are working on.[14] We saw applications in biology education,

Touch-Based Exploration of Visualizations of Spatial 3D Data

One way to address the problem of interacting with visualizations of spatial 3D data using the 2D direct-touch paradigm[1] (see the section "Data and Interaction Dimensionality" in the main article) is to employ the metaphor of interacting with the 3D space that carries the information. For example, Lingyun Yu and her colleagues' FI3D (Frame Interaction with 3D Spaces) widget uses the frame around the projected 3D data display and some well-chosen heuristics to constrain interaction (see Figure C).[2] Depending on which region of the widget the user touches and the initial direction of motion (specifically, on the frame), FI3D provides full seven-degree-of-freedom (DOF) navigation of the 3D space using one or two touch points. Most of the DOF can also be used in an isolated manner.

An additional problem with exploring spatial 3D data in a scientific context is that navigation by itself is typically insufficient for interaction. Instead, it must be combined with numerous other exploration techniques, including cutting-plane placement and manipulation, parameter specification (for example, isovalues), drilling, data selection,[3] seed point placement, and temporal interaction. All these techniques must be accessible from within the same input space.[1] So, appropriate, compatible mappings of touch input to visualization manipulations are necessary (see the section "Touch Interaction Techniques" in the main article).

Tijmen Klein and his colleagues explored such a combination of touch-based interaction techniques for fluid flow visualization (see Figure D).[4] Evaluation of the techniques showed that, although fluid-mechanics experts greatly appreciated the flexible interaction and exploration, more work was needed to provide the controlled, precise interaction and specific view configurations they required. This evaluation was performed as an observational study and provided insight about the practical use of a complex mix of visualizations and interaction techniques in a collaborative context.

Researchers have explored interfaces involving similar combinations of exploration strategies—for example, in medicine[5] and geology.[6] Ultimately, we need an integrated

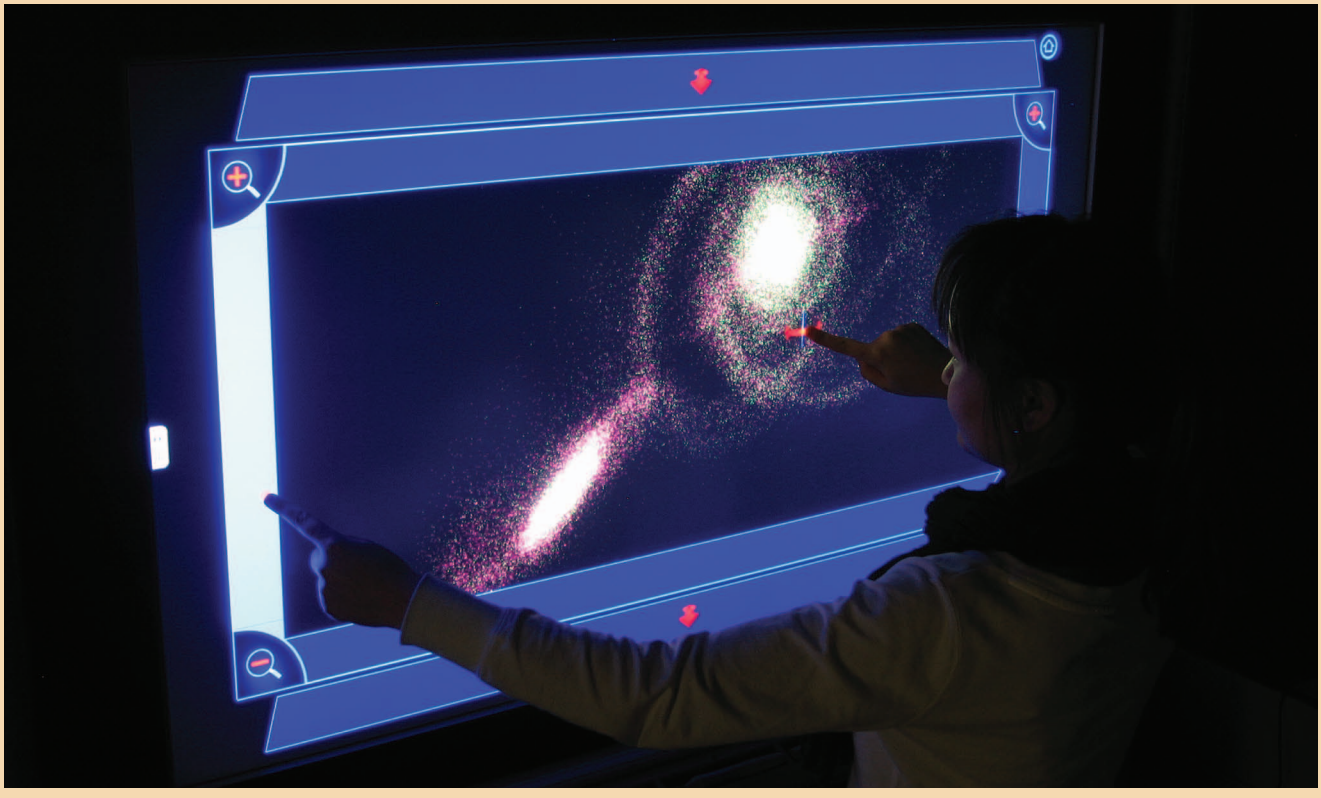

Figure C. Frame-based navigation of 3D space using the FI3D (Frame Interaction with 3D Spaces) widget.[2] FI3D provides full seven-degree-of-freedom (DOF) navigation using one or two touch points.

museum displays containing rich geographic information, software visualization on a tabletop display, medical visualization for mobile displays, and tangible magic lenses to explore data above a tabletop display. (For an example application, see the sidebar "Visualization in an Exhibition Context.")

Touch is by no means the only novel way to interact with data visualization on surfaces. For example, input modalities such as sketching, speech,

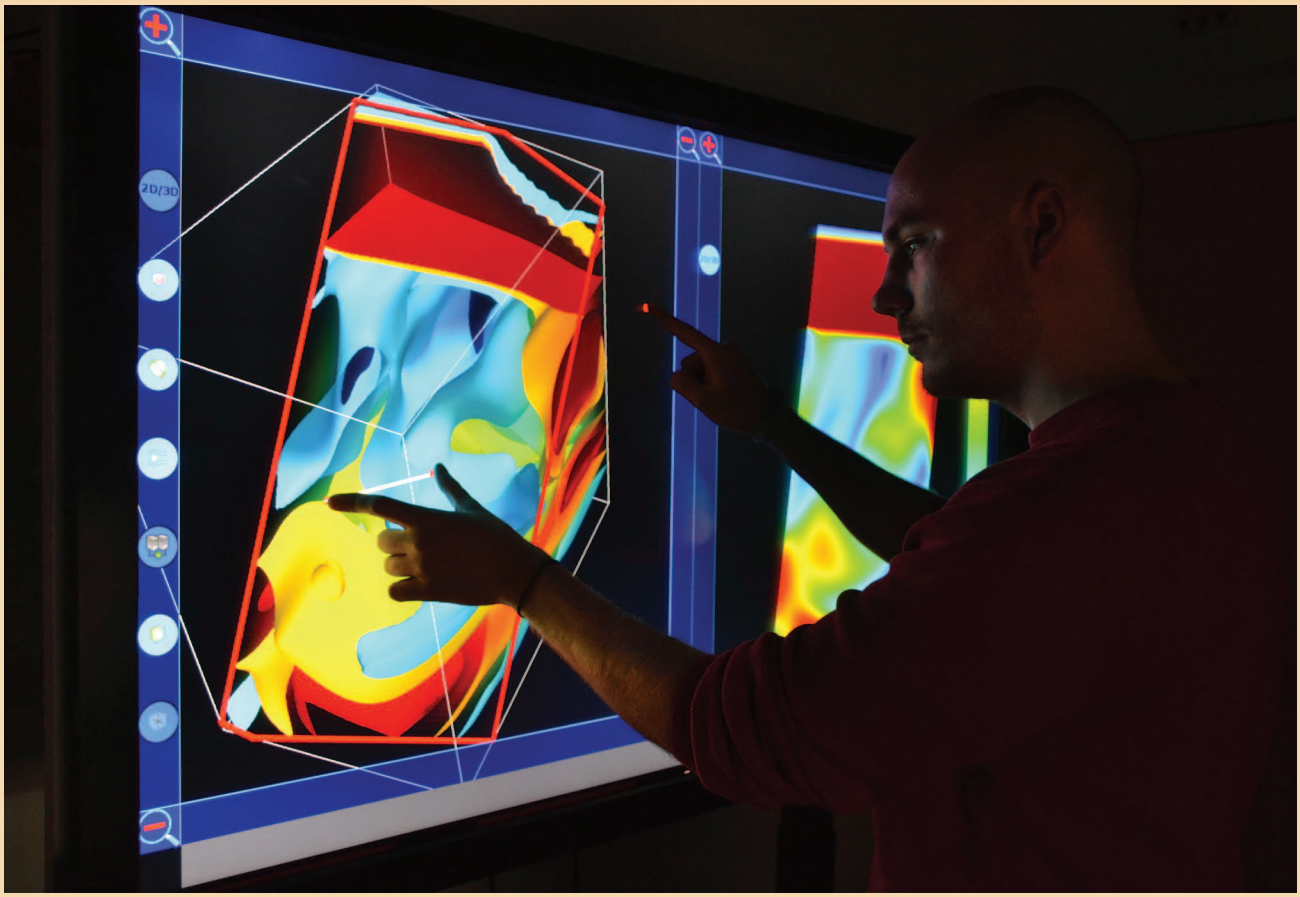

Figure D. Integration of several 3D spatial exploration techniques in a 2D input space.[4] Although fluid-mechanics experts greatly appreciated the flexible interaction and exploration, more work was needed to provide the controlled, precise interaction and specific view configurations they required.

direct-touch interaction toolkit for spatial 3D data visualization (see the section "Touch Interaction Techniques") with which users can freely apply interaction techniques for certain types of data and their dimensionalities in a variety of contexts.

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free-air gestures, and tangible devices might provide better user experiences. When properly integrated, tightly combined modalities might significantly improve the experience of using, modifying, or creating visualizations.

In the future, we'll see an even larger variety of scenarios in which visualization will be central to understanding data. New tools will give people powerful means to gain insight through visualizations anytime or anyplace using novel

displays and interaction techniques. Supporting these data analysis contexts will require solving the challenges we briefly outlined here, not to mention the additional challenges that will arise.

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