Visualization beyond the Desktop—the Next Big Thing

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Visualization researchers need to develop and adapt to today's new devices and tomorrow's technology. Today, people interact with visual depictions through a mouse. Tomorrow, they'll be touching, swiping, grasping, feeling, hearing, smelling, and even tasting data.

The rise of big data and the ever-present wish to gain an in-depth understanding of the world we live in have fueled growth and interest in all things related to visualization. Visualization's benefits are apparent. Users can see and understand their data through visual forms more easily than wading through a mass of numbers. Also, they can perform some tasks more quickly, such as ascertaining which investment has been performing better. (For more on visualization, see the related sidebar.)

So, the transformation of data into a visual form is important. However, we have the opportunity to map data to any sensory modality, not just the visual one. This idea isn't new. For instance, Geiger counters often produce an audible click for feedback, mobile phones vibrate when receiving a call, and we interact with touch devices every day. We can use these different modalities to both perceive information and interact with it.

In addition, various types of devices with different input and output modalities are becoming commercially available. Examples include head-mounted displays (HMDs) such as Google Glass and Oculus Rift and kinesthetic sensors such as Microsoft's Kinect and the Leap Motion. These devices are becoming cheaper, and the public seems to be gradually adopting them. Visualizations must adapt to exploit the capabilities of these device modalities, besides being able to process increasingly complex datasets that require more than a single mind or device to analyze.

Technological Metamorphosis

To understand how technological changes affect visualization, we must examine the main components of the visualization process. Figure 1 shows the traditional dataflow pipeline. This pipeline takes data, which might be enhanced or reduced (for example, by filtering), and maps it onto a display. Users can interact with the data to change any parameters of any step. The visualization occurs within a context or environment.

We humans use our senses to perceive information in the form of different stimuli, which we interpret and understand through cognitive processes. Specific types of information are often mapped to symbols, points, or colors that convey meaning. We perceive other types of information through more complex processes, such as proprioception, which lets us sense our body's position. Interpreting information often provides additional context and lets us, for instance, understand where we are.

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Some Background on Visualization

Visualization has been developing since Ivan Sutherland's Sketchpad and the seminal presentation of scientific visualization in 1987.[1] We can see this more recently (for example) by the introduction and development of related IEEE conferences. The first IEEE Visualization Conference was in 1990, the IEEE Information Visualization Conference started in 1995, and the IEEE Visual Analytics Conference started in 2006.

Visualization is about communicating and perceiving data, both abstract and scientific, through visual representations. To achieve this, visualizations leverage the human visual system's high bandwidth. For example, users or companies wish to understand and demonstrate trends in some data. A visual depiction of that information might let users understand the patterns and trends contained in that data more quickly than viewing the raw data.

So, engineers and scientists design visualization algorithms to map the data into a visual form or structure. Some of these structures are well known (for example, bar charts, scatterplots, and line graphs) and taught even in elementary schools. Others are lesser known (for example, treemaps and parallel coordinate plots). Every year, researchers find new ways to display data and new domains to which they can apply their skills.

For more on visualization, see *Interactive Data Visualization: Foundations, Techniques, and Applications*[2] and *Information Visualization: Design for Interaction.*[3]

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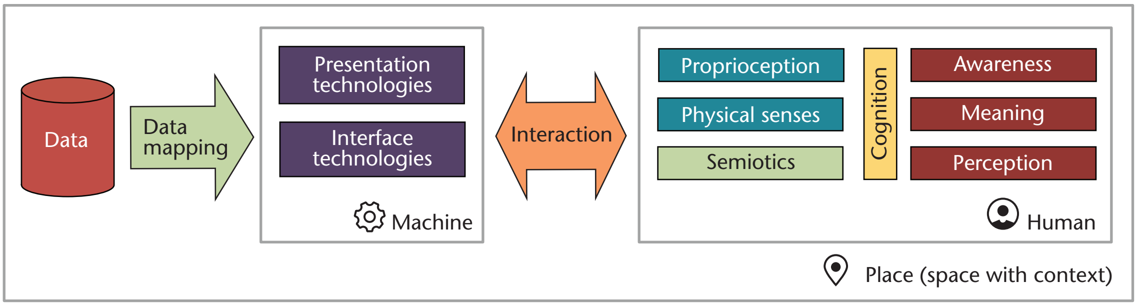


Figure 1. Visualization processes between the computer and human. Data, which might be enhanced or reduced computationally, is mapped onto perceptual variables and presented through various technologies (for example, visual or tactile displays). Various interface technologies (for example, haptics and voice recognition) allow interaction. This all occurs in a particular place—a space with context (for example, a classroom, laboratory, or means of transportation). Through this interaction and our physical senses, we feel, interpret, and understand that data, as well as our presence in space. Through perception we acquire meaning of the presented data and awareness of our context.

Data is the raw material for our insights and decisions, and lies at the beginning of the visualization process. Data has many aspects. It can be structured (such as stored in XML or Excel) or unstructured (such as a microblog message), static or temporal, or rapidly changing or slow to change. Data is getting bigger, more complex, more varied, more up-to-date, and more personal. Some data comes from ourselves as human beings. For example, affective computing (computers that respond to emotion) offers the computer insight into our well-being and emotional state.[1] The computer can change its actions depending on our behavior.

Mapping data to an appropriate visual form is a key to creating useful visualizations. This mapping depends highly on the presentation technology (for example, you might be able to map the same data to sound or temperature).

Information visualization—a subset of visualization that focuses on abstract nonphysical data—has historically targeted off-the-shelf computer hardware—that is, personal workstations often equipped with arrays of monitors for output and a mouse and keyboard for input. Accordingly, few papers at the annual IEEE Information Visualization Conference use any other computer technology than standard desktop and laptop computers. However, the possible applications of information visualization are growing to include casual users on mobile devices or nontraditional devices such as large displays, as well as teams of experts collaborating in dedicated environments. So, the range

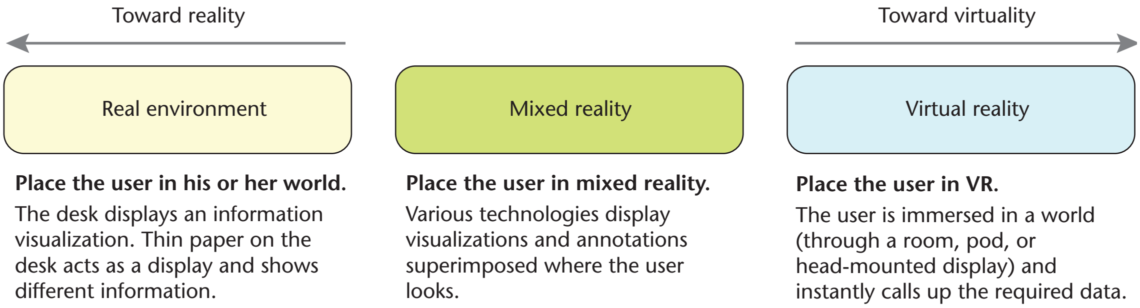


Figure 2. Paul Milgram and Fumio Kishino's reality–virtuality continuum.[5] Mixed reality has two subsets. Augmented virtuality inserts real-world views or objects into a virtual scene; augmented reality inserts virtual objects into a real-world scene.

of potential computing hardware for visualization use is also expanding. We need to look beyond the visual in visualization, to an integrated multisensory environment.

Presentation technologies range from small handheld smartphones to high-resolution immersive multiwall display systems. These technologies are improving; they have many more pixels (4K screens are now affordable by the public), are brighter (high-dynamic-range displays are being developed), and are bigger. Powerwalls with tiled displays were previously the exclusive domain of research institutes; now hobby gamers have two, four, or six screens.

Interaction lets users change parameters, select values, filter away data points, zoom in, and perform other operations on data. Interaction is becoming a more sensory experience. We pinch on tablets to zoom in and out, stroke input devices to scroll, and use our whole body to control games.

Context is also important. For instance, a visualization for military exercises must be perceived in a timely way in the field, whereas a scientist visualizing climate change can perform the tasks in his or her laboratory. Context is changing in major ways, mostly because of mobile technology. In the past, many tasks were associated with a particular location. We had to be in our office to read our email or in a meeting room to have a conference with our colleagues. Access to our files meant returning home to retrieve them from our desktop computers. This association of task and space is now less important because we can perform many tasks while we're mobile. We're much more willing to store personal information on remote repositories such as Dropbox, making that information accessible from any location to us and the people we're willing to share it with. Consequently, privacy concerns also have changed.

Inspired by Mark Weiser's vision of ubiquitous computing,[2] ubiquitous analytics strives to exploit connected devices of various modalities in an environment to enable analysis of massive, heterogeneous, and multiscale data anywhere and anytime.[3] We rely on our vision, hearing, touch, smell, and taste for interacting with the world. Because we use these senses every day, we're heavily accustomed to processing information this way. It becomes desirable for us to use the same approach to interact with our data and information. Consequently, many researchers are developing ubiquitous-analytics systems with novel multisensory interaction technologies that will let us interact with data in ways that are natural to us and therefore easy to understand. So, multisensory visualizations that employ the modern devices' various input and output modalities will be the "next big thing." We'll be able to touch, feel, smell, and even taste our data.

Although no systems currently integrate all five of the traditional senses, researchers are heading toward this goal. We appear to rely on some senses more than others, but often a combination of senses is what gives us a proper spatial awareness and understanding of our environment. Nonetheless, even though employing various senses for visualization might sound like a great idea, utilizing all the senses might not be necessary. In fact, it can lead to sensory and cognitive overload.[4] For example, consider collaborative exploration of a visualization that requires some form of notification when a user makes a significant breakthrough. Merely adding audible feedback would be sufficient, compared to involving all the senses. Moreover, most visualization systems might not gain from utilizing multiple senses unless a part of the data fits well to the sense mapping.

System designers are therefore attempting to integrate many different technologies to stimulate as many senses as possible. Researchers are investigating how our senses complement each other and under what circumstances, as well as starting to ideate and develop visions of potential systems. The technologies being developed provide much of the underpinning of what a complete system could look like.

Visions of the Future

The way that technology becomes part of our everyday life will directly affect visualization. There are many different visions of novel visualization technologies. Here, we present three visions of visualization's future. They aim to inspire you and help you ponder questions such as, what does visualization research require to achieve these visions?

These visions fit in Paul Milgram and Fumio Kishino's reality–virtuality continuum, which spans from the real (physical) to the virtual world (see Figure 2).[5] Any step between these two extremes is considered *mixed reality* (MR), which has two subsets. *Augmented virtuality* inserts real-world views or objects into a virtual scene; augmented reality inserts virtual objects into a real-world scene.

The first vision places the user in her world, which is enhanced by various modalities (see Figure 2, left). Any tool or object in that person's vicinity becomes an interface and can communicate with any other object. One focus for information visualization is an office desk on which thin "paper" acts as a display device and shows different information. On this paper, the user can view a (stereo) 3D scatterplot of the desired data, interact with it through gestures, and feel the scatterplot's points in the form of a mild tingling on her hands. She locates a dense part of the data (which feels heavy) and throws it onto the wall for closer investigation. Placing physical objects on the desk controls specific parameters. The user notices outliers and touches them, instantly highlighting related items, with a sound verifying the action. To drill down even further and filter, she clicks her fingers at a specific height, and the unwanted points drop to the floor.

The second vision places the user in MR (see Figure 2, center). Data visualizations are superimposed on the real world, as the user goes about his daily tasks. Some visualizations appear on real-world objects he sees; others are visible on his HMD. Through sound, the user's context-aware wearable informs him of the time needed to travel to work, while his colleague at a control center forwards the necessary tickets for that day and the itinerary, visible on the HMD. Textual annotations appear above nearby shops because his spouse's birthday is tomorrow. As he selects a gift, geolocated markers show which of those shops have the best prices. A subtle vibration on his wrist informs him of an incoming support call.

The final vision is a fully immersive multisensory virtual environment that stimulates all the user's senses (see Figure 2, right). The user walks into an area that transforms instantly into a "virtual visualization discovery environment." (The technology could be a room, a pod, or an HMD.) She can instantly call up any data and sculpt representations with her hands, while a virtual assistant suggests different depictions. Avatars of remotely located coworkers appear and assist. This world's physics mimics reality, in which objects have physical properties such as weight and density.

The sequence in which these visions will materialize is uncertain. We will, however, increasingly be accessing computers through natural interfaces that are "transparent" and unobtrusive, as well as various forms of multisensory interfaces.[6] To achieve these visions, complete revolutions (step changes) must take place. We're at a cusp. Technologies are maturing and have become more available and cheaper to purchase for laboratories, businesses, and homes, and people are more accepting of different modalities and technologies.

Opportunities

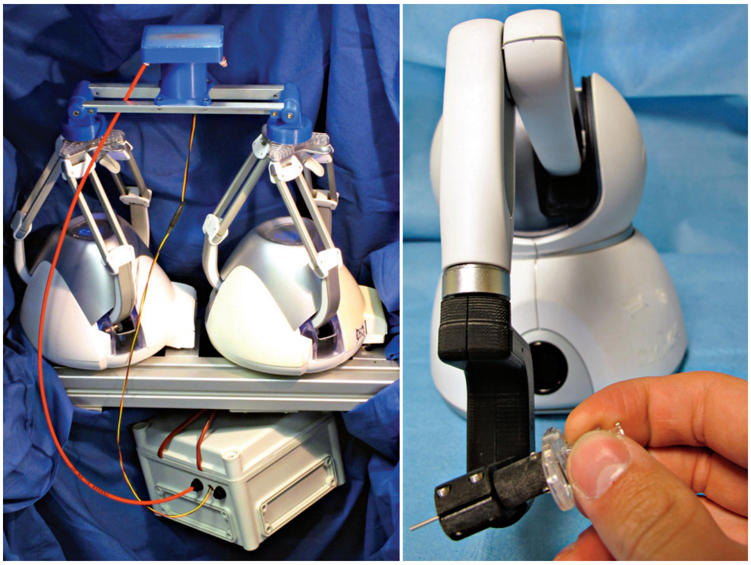
Many interaction technologies are available now and will become more widely available and affordable. Devices such as the venerable mobile phone already integrate several modalities. Smartphones and tablets engage sight, sound, and touch. For instance, a user can touch a smartphone display to interact with the device, which provides vibrotactile feedback to indicate, for example, that a text message has arrived. (For more on enabling technologies, see the related sidebar.)

Several haptic devices have become far cheaper over the past five years. Force feedback devices, once only available to and affordable by research institutes, are now available for gamers. Gaming

Enabling Technologies

The popularity of consumer electronic devices such as tablets and smartphones, as well as gaming interfaces such as Microsoft's Kinect, has transformed how we interact with computers. Using touch and gestures are the public's first steps away from mouse-based interfaces. Other enabling technologies for visualization are

- holographic displays,
- airborne haptics,
- organic light-emitting diodes,
- computer vision,
- sensor fusion,
- flexible displays,
- printed displays, and
- 3D printing.



(a) **(b)**

Figure 3. Two haptic devices used in Bangor University's PalpSim project. (a) Two modified Novint Falcon force feedback devices for training femoral palpation. (b) The Geomagic Touch (formerly the Sensable Phantom Omni) force feedback device for training needle insertion. It uses a real needle hub for increased realism. (Source: Tim Coles and Nigel W. John, Bangor University; used with permission.)

controllers such as the Wii Remote and PlayStation Move provide vibrotactile feedback when a player hits the ball in a game of tennis, for example. Devices such as the Novint Falcon (see Figure 3), which employ haptic force feedback, offer opportunities for multisensory visualization.[7] Multiple-participant tactile tables such as those that use Microsoft PixelSense and the DiamondTouch are also available to consumers.

Communication technologies will also enhance visualization capabilities, especially for multisensory systems. Many gaming consoles already offer multiparticipant remote gaming. Through telecollaboration, visualization capability will be transmitted and exchanged to provide an immersive experience. This will further enable multiple clients to discuss different viewpoints. For instance, emergency services staff will be able to remotely view and interact with visualizations and simulations of different scenarios.

The recent surge in hardware for tracking user activity such as Vicon setups (www.vicon.com) has led to interaction using *proxemics*. Proxemics, introduced by Edward T. Hall, concerns a user's or physical object's spatial attributes, including position, distance, orientation, movement, and identity.[8] Human–computer interaction (HCI) is already using models that automatically interpret these attributes to trigger actions on a computer interface.[9] Initial attempts to employ this interaction model in visualizations have been successful.[10] Further research to fully explore the design choices for proxemic interaction and to study this implicit interaction style's tradeoffs would be helpful in designing intuitive, efficient interaction models that support both individual and collaborative data analysis.

In particular, the research community has begun focusing on four types of visualization environments: casual, mobile, Web, and dedicated.

Casual

The fledgling field of casual visualization[11] will continue to grow as our homes become increasingly equipped with integrated, pervasive input and output modalities. Continuing the trend of "visual displays everywhere," a long-term vision for casual visualization is *appropriated surfaces*.[12] These surfaces abandon the device's input and output surfaces in favor of surfaces in the surrounding world. They allow visual data analysis on any topic and dataset of interest to the user. For example, the Xbox Kinect motion capture camera (modestly priced at approximately US$ 100) can recover the pose of one or two players simultaneously in real time. With over 40 million Xboxes in people's homes worldwide, tremendous potential exists for turning the standard living room into a dedicated visualization environment.

Mobile

Mobile devices such as smartphones and tablets have an intrinsic conflict. Whereas miniaturization is letting us build ever-smaller devices, human factors stipulate that input and output surfaces should be as large as possible.[12] This is particularly true for visualization applications, which live and die by their visual displays. To deal with this, mobile visualizations could adapt to these device modalities and use compact representations of data with aggregates and overviews when needed, to trade information for screen space.[13]

Web

A major barrier to achieving ubiquitous computing is the lack of a unifying software infrastructure[14] that can enable context awareness and the sharing of user input, interaction, and other resources among devices. For instance, typical collaborative visualizations[15] spanning multiple devices and platforms must be able to support both individual views that react to a single user's input and collaborative views that react to multiple users. Similarly, to propagate visualization research and invite a social style of data analysis and opinion sharing, we need sophisticated tools to capture users' visualization state and interaction at any time. Toward those ends, the Web can be the most platform-independent way to build and share visualizations, thus achieving ubiquity and supporting collaboration.

Dedicated

Eventually, researchers will combine different input and output surfaces to create coherent, large-scale dedicated visualization environments. Although these environments will be expensive and somewhat difficult to use, they'll enable intense, collaborative data analysis on a scale not previously possible with standard desktop systems.

Technologies for building such environments already exist. Tiled LCD displays (or gigapixel displays) are becoming increasingly common. 3D motion capture cameras allow for real-time motion capture with high resolution and low noise levels. In addition, hobbyists can now build multitouch tabletops (see Figure 4).[16]

Figure 4. A 108-inch multitouch table, part of Edinburgh Napier University's Interactive Collaborative Environment. Technologies such as this will lead to coherent, large-scale dedicated visualization environments. (Source: Institute for Informatics and Digital Innovation; used with permission.)

These environments (Figure 5 shows another example) can certainly gain from well-designed post-WIMP (windows, icons, menus, pointing devices) models for interacting with shared spaces and individual displays. Coupling visual interfaces and propagating interaction across multiple devices in these environments can be achieved at the software level through sophisticated middleware tools such as Hugin.[17]

Figure 5. A multidevice environment with mobile devices and a shared display space. The mobile devices provide individual views that respond to a single user's input; the shared displays contain collaborative visualizations. These dedicated visualization environments are becoming increasingly common and can benefit from guidelines in casual, Web, and mobile visualization research, to support data analytics using multiple device modalities.

A Roadmap to the Future

To achieve this overall vision, we must focus on the following HCI paradigms and address their challenges.

Fluid Interaction

As the research community begins exploring information visualization in casual, mobile, Web, and dedicated environments, researchers have been developing more natural and fluid interfaces. We humans make fluid motions, we easily draw strokes with a pen on a paper, our gestures are dynamic and animated, and our sound generation is continuous. However, computer interfaces don't behave in continuous manner. For instance, we click with a mouse, pull down menus, or type with a keyboard.

In the near future, we'll be able to be immersed in a virtual world and interact with virtual objects.

Recent advancements in natural-language processing, tactile displays, kinesthetic sensors, and sensor fusion are gradually letting us interact with technology in a more natural and fluid—albeit still primitive—way that involves more senses. Consequently, as HCI research turns its attention to multisensory interface mechanisms, we should see their more frequent application and use in visualization scenarios.

Toward that goal, we need a holistic theory of multisensory visualization.[18] We need to consider how we can achieve sensory integration and how cross-modal interference occurs—especially how different sensations interfere with or reinforce each other. Furthermore, we need to determine the perceptual variables for multisensory visualization in different scenarios.

Finally, we need to create technologies that work together. This involves not only the ergonomics of how they work together but also how they complement each other and how developers can create suitable software for them.

Transparency

As interaction with visualizations becomes more natural, they'll become more pervasive and transparent. We'll see input and output technology starting to be integrated into our environment.

One way of this occurring is through appropriated surfaces such as handheld projectors, skin input surfaces, and high-precision optical tracking of the surrounding world. This approach has a poetic symbolism for visualization, which relies heavily on *external cognition*,[19] or what has been called "knowledge in the world." So, we'll see a paradigm shift to a culture in which we're surrounded by information and the supporting technology is transparent to us.

Nonetheless, we'll want to keep some aspects of our daily life private. Inevitably, embedding information in the environment has implications for privacy and obtrusiveness, as visualizations become public and the information is available to everyone present. Offering personalized information, whether immediately through displays embedded in the environment or through smartphones or wearables, requires a certain level of context awareness and appropriate filtering. Context-aware visualization systems will need to answer questions such as, Is the information being presented to the right person? Is that information appropriate for the user's context and preferences?

To some degree, this already occurs with smartphones, where we have access to personalized views of our bank accounts, email, social networks, and so on. Wearable, context-aware displays such as Google Glass can offer even more personal views of specific information, away from prying eyes. Both device types can serve to identify the user in an environment.

Consequently, visualization researchers should focus on two major directions. First, they should incorporate appropriate visualizations for each form of display, whether wearable, handheld, or embedded in the physical world. The first two display types have a small footprint, whereas the third type can include large, high-resolution displays. Second, visualization researchers should explore the resulting interaction affordances, which are different in each case. Doing so, to create novel ways to interact with new types of visualization, will enable new forms of data exploration.

Integrated Sensory Interaction

The aforementioned advances in display technology and miniaturization, and the expectation of affordable, consumer HMDs such as the Oculus Rift, have revived the field of VR. In the near future, we'll be able to be immersed in a virtual world and interact with virtual objects—touch them, feel their texture and weight, and pick them up and move them.

Such immersive environments will let us hold virtual meetings and communicate more naturally, regardless of our physical location, saving time and resources previously spent on travel. These technologies exist today in various forms (teleconferencing, virtual worlds, and so on). However, we expect that future immersive displays and multisensory interaction interfaces will further enhance the user experience and sense of presence. By 2030, most homes will have some form of immersive displays, which will likely have become a modern replacement for TVs and probably won't cost more than an average TV does today. The technology will become essential to our lives, enhancing communication, work, and entertainment. In this new, immersive world, visualization will form an important paradigm for any form of analysis and decision making, from performing simple tasks such as searching for the best prices to making complex financial decisions.

So, visualization researchers should exploit the experience gained over the last two decades in VR research (often ignored in the media), while continuing to apply the ever-evolving VR technology to visualization systems. Moreover, they should treat immersive worlds as not only presentation mediums but also data sources, especially regarding interaction, collaboration, and sense of presence.

Toward Mixed Reality

An even more interesting prospect, different from the exclusivity that a VR environment entails, is that of MR. As we mentioned before, MR presents information in a synthetic world in which computer-generated and physical objects coexist. This concept somewhat extends ubiquitous computing, often regarded as the antithesis of VR.[20] MR enhances our physical world in numerous, subtle, and often invisible ways.[21]

MR artifacts aren't necessarily visible but are perceivable, much as a wireless connection is invisible, yet we can be aware of its existence. Moreover, these artifacts offer different levels of information that in turn can be perceived through various modalities. We're therefore immersed in an information space that can extend beyond our immediate physical world while providing context-aware information and allowing natural, fluid interaction.

Evan Barba and his colleagues argued that MR research, which currently is driven mainly by smartphone technology, must focus on all aspects of human cognition, not just vision, as it has been doing.[20] They added that MR space (physical or synthetic) acquires meaning through context and that different technologies and their quality directly affect interaction capabilities.

This expanded version of perceptualization is intrinsic to the future manifestation of visualization. We can safely assume that visualization will use future MR systems as a canvas. As we rely on visualization for gaining insight and making decisions, and as MR slowly enhances our world, much like in Vernor Vinge's novel *Rainbows End*, we expect to see MR systems encompassing different modalities and fluid interfaces. These systems will be accessible through physical and synthetic displays and interaction mechanisms, as well as wearable devices such as Google Glass.

Moreover, novel types of natural interactions are becoming more widespread. Affective computing that employs different modalities (such as electroencephalography) could be used to control different devices. It could also change how visual depictions are displayed or respond to user input.[22]

As we start using visualization technology for everyday communication, productivity, and entertainment, the adoption rate for novel interaction technologies will increase. The increased demand for these technologies will lead to decreased production costs and increased competition, which will both lead to much cheaper products.

It's an exciting time for HCI research. New input and output modalities are providing intriguing new ways to interact with computers and offer new opportunities and challenges for visualization. Nevertheless, these new devices are just tools. The responsibility of how to best use them lies in our hands—those of visualization researchers, designers, and practitioners worldwide.

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