Visualization Beyond the Desktop - The Next Big Thing

Jonathan C. Roberts ▪ *Bangor University*
Panagiotis D. Ritsos ▪ *Bangor University*
Sriram Karthik Badam ▪ *University of Maryland, College Park*
Dominique Brodbeck ▪ *University of Applied Sciences Northwestern Switzerland*
Jessie Kennedy ▪ *Edinburgh Napier University*
Niklas Elmqvist ▪ *University of Maryland, College Park*

Visualization has risen in popularity over the past two decades, especially due to the need to analyze large and complex datasets. The rise in popularity of big data, and the ever-present wish to gain in-depth understanding of the world we live in, have all fueled a recent growth and interest in all things related to *visualization*.

Visualization is coming of age: with visual depictions being seamlessly integrated into documents and data visualization techniques being used to understand datasets that are ever-growing in size and complexity, the term visualization is becoming used in everyday conversations. But we are on a cusp; visualization researchers need to develop and adapt to today's new devices and tomorrows technology. Today, we are interacting with visual depictions through a mouse. Tomorrow, we will be touching, swiping, grasping, feeling, hearing, smelling and even tasting our data. The next big thing is multi-sensory visualization that goes beyond the desktop.

Visualization is not a new concept. Since Ivan Sutherland's Sketchpad and the seminal presentation of scientific visualization in 1987,[1] the field has been developing. We can see this more recently (for example) by the introduction and development of conferences in the IEEE series. In 1990 we saw the first "IEEE Visualization" conference, then Information Visualization started in 1995, and more recently "Visual Analytics" in 2006. Before we get into talking about multi-sensory visualization that utilizes various senses such as hearing, smell, and touch along with sight, both as input modalities and for interaction feedback, let's start at the beginning and define visualization itself.

The field of visualization is about perception and communication of data, both abstract and scientific, through graphical or visual representations of the data. Visualizations leverage the high bandwidth nature of the human visual system to achieve the aforementioned goal. (For more information about visualization we refer the reader to books on visualization such as Ward et al.[2] and Spence[3]). For example, users or companies wish to understand and demonstrate trends within some data. A visual depiction of that information would enable a user to understand the patterns and trends contained within that data, arguably, faster than by viewing the raw data itself. Engineers and scientists therefore design different visualization algorithms to map the data into a visual form or structure. Some of these visualization algorithms are well known (barcharts, scatterplots, line graphs etc.) and taught in junior schools, while others are lesser known (treemaps, parallel coordinate plots). Every year, researchers in the field find new ways to display their data and new domains to apply their skills.

The benefit of visualization is quite apparent: users can see and understand their data through visual forms more easily than wading through a mass of numbers; the visual depiction enables the user to perform a task, such as to ascertain which investment has been performing better, quicker.

Therefore, the transformation of data into something *visual* is important. But here is also the opportunity. It is possible to map the data into *any* sensory-modality, not just the visual one. This idea is not new. For instance, Geiger counters often have an audible click for interaction feedback, mobile phones vibrate when a call is received, and everyday we are interacting with touch devices. We can both use these different modalities to perceive information as well as to interact with it.

Visualization as a research topic is coming of age, spurred by our need to understand ever-growing datasets. In addition, various types of devices with different input and output modalities have been recently becoming commercially available. Some examples include head-mounted displays (HMDs) such as Google's Glass and the Oculus

Rift and kinesthetic sensors such as Microsoft's Kinect and the Leap Motion. These devices are becoming cheaper and seem to be, gradually, receiving widespread adoption from the public. Visualizations need to adapt in order to exploit the capabilities of these device modalities on top of becoming and remaining capable of processing increasingly complex datasets that require more than a single mind or device to analyze.

Technological Metamorphosis

To understand how technological changes affect visualization we need to look into the main components of the visualization process itself. The traditional dataflow pipeline takes (a) *data* that may be enhanced or reduced (e.g., by filtering) that is (b) *mapped* onto (c) a presentation display; (d) the user can *interact* with the data to change any parameters of any step. Finally, (e) this visualization occurs within a context or environment (i.e., a *place*).

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

Data is the raw material for our insights and decisions, and lies at the beginning of the visualization process. There are many aspects to data; it can be structured (such as stored in XML or Excel) or unstructured (such as a microblog message), it can be static or temporal, rapidly changing or slow to change. While there are many reports discussing the challenges with big data, this is not the focus of our paper. Suffice to say, data are getting bigger, more complex, more varied, more up-to-date, and more personal. In fact, some data are coming from ourselves as human beings. Affective computing offers the computer an insight into our well-being and state of emotion. The computer can change it's actions depending on our behaviour.

Mapping the data to an appropriate visual form is a key to creating a useful visualization. This mapping depends highly on the presentation technology (e.g., the same data could be mapped into sound or into temperature).

The field of information visualization (InfoVis)—a subset of visualization that focuses on abstract non-physical data—has historically targeted off-the-shelf computer hardware, i.e., personal workstations often equipped with arrays of monitors for graphical output, and a mouse and keyboard for input. Accordingly, very few papers at the annual IEEE Information Visualization (InfoVis) conference use any other computer technology than standard desktop and laptop computers. However, as the possible applications of InfoVis grow to include casual users on mobile or non-traditional devices, such as large displays, as well as teams of experts collaborating in dedicated environments, the range of potential computing hardware for visualization usage is expanding as well. We need to look beyond the visual in visualization, to an integrated multi-sensory environment.

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

Interaction enables users to change parameters, select values, filter away data points, zoom in, and perform other operations on the data. Interaction is becoming a more sensory experience: we are pinching on tablets to zoom in and out, swiping on input devices to scroll, and using our whole body as an interaction device for home gaming.

Context is also very important. For instance, a visualization that is required for the military needs to be perceived in a timely way and in the field, whereas a user visualizing climate change can perform the tasks in their laboratory. One of the major changes that we see nowadays is how context is changing, mostly due to the use of mobile technology. In the past many tasks were associated with a particular location. We had to be in our office to read our emails, 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. Nowadays, this association of task and space is less important as many tasks can be done while mobile. We are much more willing to store personal information on remote repositories like Dropbox, making them accessible from any location, from us and people we are willing to share it with. Consequently privacy concerns also have changed.

Inspired by Mark Weiser's vision[4] of ubiquitous computing in the realm of data analytics, ubiquitous analytics[5] envisions utilizing connected devices of various modalities in an environment to enable analysis of massive, heterogeneous, and

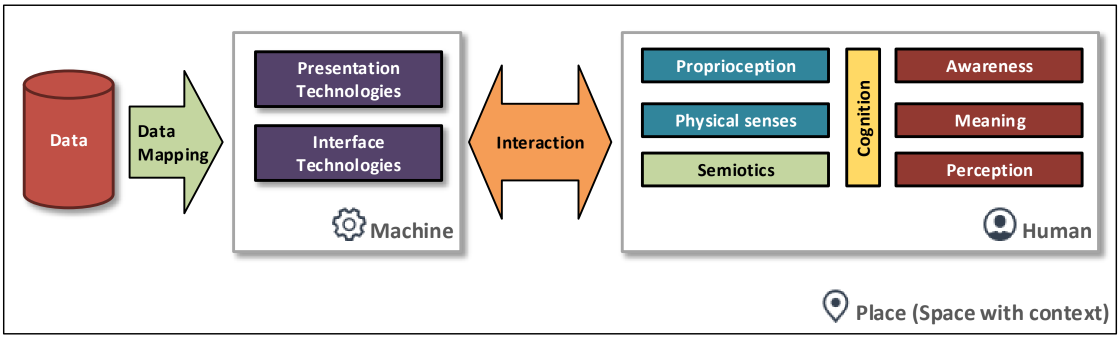


Figure 1: *Visualization processes between the computer and the human. Data, that may be enhanced or reduced computationally, are mapped onto perceptual variables and presented through various presentation technologies (e.g., visual displays, tactile displays etc.). Various interface technologies allow interaction (e.g., haptics, voice-recognition etc.). This is all done in a particular place, i.e., a space with context (e.g., classroom, laboratory, on means of transportation etc.). Through this interaction and by means of 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.*

multi-scale data anywhere and anytime. We, as humans, rely upon our senses of vision, hearing, touch, smell and taste for interacting with the world around us. As we use these senses everyday, we are heavily accustomed to processing information this way; it becomes very desirable for us to use the same approach to interact with our data and information. Consequently, many researchers are developing new ubiquitous analytics systems with novel multi-sensory interaction technologies that will allow us to interact with data in ways that are natural to us and therefore easy to understand. Therefore, multi-sensory visualizations that utilize the various input and output modalities of modern devices will be the “next big thing”. We will be able to touch, feel, smell, and even taste our data.

Although there are not yet any systems that integrate all five of the common senses, several researchers are heading towards this goal. In actuality, we appear to rely upon some of our senses more than the others, but it is often a combination of senses that gives us a proper spatial awareness and understanding of the environment around us. Nonetheless, even though utilizing various senses for visualization may sound like a great idea, utilizing all the senses may not be required, as, if overdone, can lead to sensory and cognitive overload.[6] For example, in a collaborative exploration of a visualization, where some form of indication is required when one of the users makes a significant breakthrough, merely adding audible feedback would be sufficient, compared to involving all senses. Moreover, most visualization systems may not gain from utilizing multiple senses unless there is a part of the data that fits well to the sense mapping.

System designers are therefore attempting to integrate many different technologies in order to excite 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. Thus, the use and integration of technologies that stimulate several of our senses is a growing area and new research direction. Many different technologies, providing much of the under-pinning of what a complete system could look like, are being developed.

The Vision

Knowing what the future will behold is a difficult endeavor. Futurologists spend much time researching what institutions and companies are developing, and how money is being invested. There are certainly many futurologists and media writers discussing technology, commenting on promising technologies and debating over future business models.

Likewise, science fiction, spanning from Jules Verne’s work, to modern examples like Vernon Vinge’s Rainbows End has always been a source, and an expression, of inspiration and vision. Films, describe visions of future technologies. Characters in ‘Minority Report’, wearing wearables or using tactile computer visualization interfaces, heads-up displays (HUDs) portrayed in ‘Iron Man’ or immersive virtual worlds like in ‘The Matrix’ or the much earlier Star Trek’s Holodeck provide, and express, inspiration and vision.

The way that technology becomes part of our every day life will have direct impact on visualization. There are many potential visions to use novel technologies for visualization. Following, we present three potential ‘visions’ of the future of visualization that fit with Milgram and Kishino’s Reality-Virtuality continuum (see inset, right). The presented visions are deliberately aspirational, and are included to inspire and help us ponder questions such as 'what is required in visualization research to achieve these visions'.

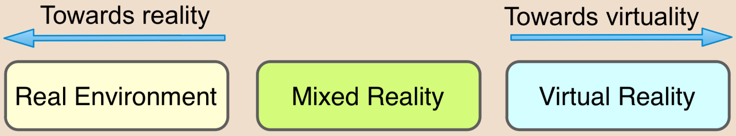
The first vision places the user in their world, which is enhanced by various modalities (see Figure 2(a), shown in the inset). Any tool or object they have in their room becomes an interface and can communicate with any other object. The desk in their office provides one focus for the information visualization, where thin paper on the desk acts as a display device and shows different information. On this 'paper' they can view a (stereo) three-dimensional scatterplot of their data, interact with it through gestures and hand movement and feel the scatterplot's points, in the form of light tactile tingling, as they roll over their hands. They locate a dense part (which feels heavy) and throw it onto the wall for closer investigation. Placing physical objects on the nearby desk controls specific parameters. Users notice outliers that they touch, instantly highlighting related items, with the action followed by a sound verification. To drill down even further and filter, the user clicks their fingers at a specific height, and the unwanted points drop down to the floor.

The second vision places the user in the mixed-reality world (Figure 2(b)). Data visualizations are superimposed on the real world, as the user goes about their daily tasks. Some of these visualizations are displayed on real-world objects, where the user gazes on, others are visible through a wearable HMD. Their context-aware wearable informs them through sound on the time needed to travel to work, while their colleague in a control-center forwards the support tickets for that day and a planned route for visits, visible on their HMD. Textual annotations are displayed above nearby shops, as their spouse's birthday is tomorrow. As the user selects a gift, geo-located markers show where the best price can be found, nearby. A subtle vibration on their wrist informs them they got a support call.

The final vision is a fully immersive multi-sensory virtual environment (MS-VE), which excites all of the users senses (Figure 2 (c)). The user walks into a room that transforms instantly into a 'virtual visualization discovery environment'. (The technology could be a room, pod or HMD). The user can instantly 'call up' any data and sculpt representations by their hands, while the avatar of a virtual assistant helps them by making suggestions of different depictions. Avatars of remotely-located co-workers appear and assist. The physics of the world mimics reality, where objects have physical properties, such as weight and density.

Mixed Reality Continuum

Milgram and Kishino's Reality-Virtuality continuum[1] spans between the entirely real (physical) to the entirely virtual, computer generated world (Figure 2). Any step between these two extremes is defined as Mixed Reality (MR), encompassing the subsets of Augmented Virtuality (AV), where real world views or objects are inserted into a virtual scene and Augmented Reality (AR), where virtual objects are inserted into real world scene.



(a) Place the user in their world *The desk displays an information visualization, thin paper on the desk acts as a display device and shows different information*

(b) Place the user in MR *Various technologies display visualizations and annotations superimposed where the user looks*

(c) Place the user in VR *The user is immersed in a world, (through a room, pod or head mounted display) and instantly calls-up required data*

Figure 2: *Milgram and Kishino's reality-virtuality continuum.*

References

1. Paul Milgram and Fumio Kishino. "A Taxonomy of Mixed Reality Visual Displays". *IEICE Transactions Information Systems*, E77-D(12):1321-1329, 1994

The sequence in which these visions will materialize is uncertain. We will, however, increasingly be interfacing computers through natural interfaces that are 'transparent' and unobtrusive as well as multi-sensory interfaces[7] that integrate input and output that engage all senses, and comes in various different forms. Consequently to achieve these visions for visualization, complete revolutions (i.e., step changes) will need to take place. We are currently at a timely cusp, where technologies are maturing and have become more available and cheaper to purchase in the laboratories, businesses and homes, while there is more acceptance on the use of different modalities and technologies, than in the past.

Opportunities

Many interaction technologies are available now and they will be more available and affordable in the future. Devices such as the venerable mobile phone already integrate several modalities. Mobile devices such as smartphones and tablets engage sight, sound and also touch, where for instance, a user can touch the display to interact with the system, and the device provides vibrotactile feedback to the user to denote (say) a text message has arrived. Certainly, the cost of several haptic devices has already fallen drastically over the past five years. Force-feedback devices, once only available and affordable by specific research institutes, are now available for gamers. Gaming controllers such as the Wii Remote and PlayStation Move provide vibrotactile feedback when a player (say) hits the ball in a game of tennis. Devices such as the Novint Falcon (see Figure 3), employing haptic force-feedback, offer opportunities for multi-sensory visualization.[8] Multiple participant tactile tables such as Microsoft PixelSense and DiamondTouch are also available for consumer use.

Enabling Technologies

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

- Holographic Displays
- Airborne Haptics
- Organic light-emitting diode
- Computer Vision
- Sensor Fusion
- Flexible displays
- Printed displays
- 3D printing

Communication technologies will also enhance visualization capabilities especially for multi-sensory systems. Many of the gaming consoles already offer multi-participant remote gaming experiences. Through remote telecollaboration, visualization capability will be transmitted and exchanged to provide an immersive visualization experience. This will further enable multiple clients to discuss different viewpoints. For instance, emergency service 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 (http://www.vicon.com) have lead to a new mode of interaction using *proxemics*. Proxemics,[9] first introduced by Edward T. Hall, concerns with the spatial attributes of a user or a physical object including position, distance, orientation, movement, and identity. Interaction models that automatically interpret these spatial attributes (or proxemics[10]) to trigger actions on a computer interface are already in use in human-computer interaction (HCI). While initial attempts to utilize this interaction model in a visualization setting have been successful[11] further research to fully explore the design choices for proxemic interaction and to study the tradeoffs of this implicit interaction style can be helpful in designing interaction models that are intuitive, efficient, and support collaborative as well as individual analysis of data.

The research community has begun to draw its attention to the 'Casual, Mobile, Web and Dedicated' visualization environments—a shift we foresee will become more apparent in the next few years. There is an evident trend in *broadening* the spectrum of computing platforms used for visualization, beyond the desktop computer. Miniaturization has allowed us to gradually employ *small*, *untethered*, *portable* devices—i.e., smartphones, tablets, and *wearables* such as smart watches—to perceive information, as well as generate more data. Likewise, progress in display technologies allows us to integrate high-resolution displays into dedicated visualization environments. Consequently, through this pervasiveness of technology, visualization systems find their way into our everyday lives.

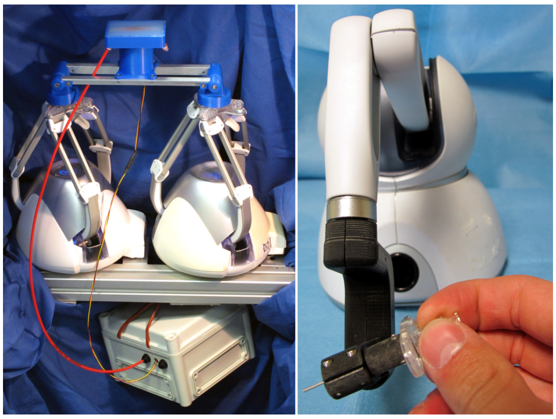


Figure 3: *Haptic devices used in the Bangor PalpSim project for training Femoral Palpation and Needle Insertion. Left: Two modified Novint Falcon force-feedback devices for a pulse palpation simulation. Right: Needle modification using Geomagic's Touch (formerly Sensable Phantom Omni) force feedback device — a real needle hub has been fitted for increased face validity. Pictures courtesy of Tim Coles and Nigel W. John, Bangor University.*

Casual visualization. We believe that the fledging field of casual visualization[12] will continue to grow as our very homes become increasingly equipped with integrated and pervasive input and output modalities. Continuing the trend of "visual displays everywhere," a long-term vision for casual visualization is appropriated surfaces[15] in our homes that allow for visual data analysis on any topic and dataset that is of interest to the user. As a case in point, the Xbox Kinect motion capture camera (modestly priced at 90 USD for gamers) is capable of recovering the pose of up to two players simultaneously and in real-time. With over 40 million Xbox units embedded in people's homes worldwide, it is clear that tremendous potential exists for turning the standard living room into a dedicated visualization environment in its own right.

Figure 4: *A multi-device environment with mobile devices and shared display space. While the mobile devices provide individual views that respond to the interaction of a single user, 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, in order to support data analytics using multiple device modalities.*

Another aspect of casual visualization is to support casual experts, who have expertise in fields other than visualization and utilize them for various domain specific datasets such as genomics and product design repositories.

Web Visualization. A major barrier against achieving Mark Weiser's vision of ubiquitous computing[4] (Ubicomp) is the lack of a unifying software infrastructure[13] that can enable context awareness as well as sharing user input, interaction, and other resources among the devices. For instance, typical collaborative visualizations[14] spanning multiple devices and platforms require provisions for individual views that react to the interaction of a single user as well as collaborative views that react to multiple users. Similarly, in order to propagate visualization research and also invite a social style of data analysis and opinion sharing, there is a need for sophisticated tools to capture the visualization state and interaction of the users at any time. In this aspect, the web can be the most platform-independent way for building and sharing visualizations, thus achieving the predicted ubiquity, and support collaboration among users.

Mobile visualization. Smartphones and handheld tablets are becoming increasing integrated into our everyday lives. However, these mobile devices have an intrinsic conflict: while miniaturization now enables us to build ever-shrinking devices, human factors stipulate that input and output surfaces should be maximized in size.[15] This is particularly true for visualization applications, which live and die by their visual displays and thus need to be as large as possible in size. To counter this, mobile visualizations[16] can be built to adapt to these device modalities and utilize compact representations of data with aggregates and overviews when needed, to trade information for screen space.

Dedicated visualization environments. By the same token, we predict that the specialization will continue on the other end of the spectrum through the creation of large-scale dedicated visualization environments consisting of many different input and output surfaces, all connected into a single coherent visual environment. While expensive and somewhat heavy-weight to use, these dedicated visual environments will enable intense and collaborative data analysis on a scale not previously possible for standard desktop systems.

Technologies for building such environments exist already today: 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, and multi-touch tabletops (see Figure 5) can now be built by hobbyists.[17]

These environments (Figure 4) can certainly gain from well designed post-WIMP interaction models for interacting with the shared spaces and individual displays. Coupling visual interfaces and propagating interaction across multiple devices in the aforementioned environments can be achieved at a software level through sophisticated middleware tools such as Hugin.[18]

A Roadmap to the Future

To achieve our vision we need to focus on a series of HCI paradigms, presented in this section and address their respective challenges.

Fluid Interaction

As the research community begins to explore information visualization in causal, mobile and dedicated environments there are some initial efforts in developing more natural and *fluid* interfaces. As humans we are more fluid in our motions; drawing strokes with a pen on a paper is easy, our gestures are dynamic and animated, and our sound generation is continuous. However, computer interfaces do not behave in continuous manner. For instance, we click with a mouse, we pull down menus, or we type with a keyboard.

Recent advancements in natural language processing, tactile displays, kinesthetic sensors and sensor fusion gradually allow us to interact with technology artifacts in a more natural and fluid—albeit still primitive—way that involves more

Figure 5: *The 108 inch multi-touch table at Edinburgh Napier University, part of their Interactive Collaborative Environment (ICE). Images courtesy of Institute for Informatics and Digital Innovation.*

senses. Consequently, as HCI research turns its attention to multi-sensory interface mechanisms, we expect to see their application and use in visualization scenarios more frequently.

Towards that goal, a holistic theory of multi-sensory visualization needs to be developed[19] as we need to consider how sensory integration is achieved and how cross-modal interference occurs—especially how different sensations interfere or reinforce each other. Furthermore, we need to determine the perceptual variables for multi-sensory visualization in different scenarios.

Last but not least, we need to create technologies that work together. Not only the ergonomics of how they are being used in synergy, but also how they complement with each other and how a developer would create suitable software for them.

Transparency

On the other hand, as visualization will become more natural to interact with, it will become more pervasive and transparent. We will begin to see input and output technology starting to be integrated into the environment around us: it will weave its way into our everyday life and become ubiquitous, as Weiser describes.[4]

One way of this occurring is through *appropriated surfaces*,[15] where input and output surfaces on the device itself are abandoned in favor of surfaces in the surrounding world. Examples of appropriated surfaces include handheld projectors, skin input surfaces, and high-precision optical tracking of the surrounding world. In a way, this approach has a poetic symbolism for visualization, which heavily relies on the concept of *external cognition*,[20] or what has been called "knowledge in the world." As a result we will see a paradigm shift into a culture where we are surrounded by information and the supporting technology will become transparent to the end user.

Nonetheless, as visualization becomes part of our daily life, there are aspects of the latter that we will want to remain private. Inevitably, embedding information in the environment has implications on privacy and obtrusiveness, as visualizations become public and the information available to everyone present. Offering personalized information, whether immediately through displays embedded in the environment or through smartphone or wearable devices requires a level of context awareness and appropriate filtering. Questions such as, is the information presented to the right person or is it appropriate to the user's context and preferences will need to be answered by context-aware visualization systems.

To some degree this occurs at the moment on smartphones, where we have access to personalized views of our bank accounts, email, social networks etc. Wearable, context-aware displays such as Google Glass can offer even more personal views on specific information, away from the prying eyes. Both device types can be used for identification of the user in an environment.

Consequently, there are two major directions that we feel visualization researchers should focus on. Firstly, incorporate appropriate visualizations for each form of display, whether wearable, handheld or embedded in the physical world. Notably, the first two have small footprint whereas the third case can include high-resolution, physically large displays. Secondly, explore the resulting interaction affordances, which are different in each case. Doing so, in order to create novel ways that allows us to interact with new types of visualization will enable new forms of data exploration.

Integrated Sensory

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

Such immersive environments will allow us to hold virtual meetings and communicate in a more natural way, regardless of our physical geographic location, saving time and resources traveling across the world to meet. Although these technologies exist today in various forms (teleconferencing, virtual worlds etc.) we expect future immersive displays and multi-sensory interaction interfaces to enhance the user experience and sense of presence. By 2030, most homes will have some form of immersive displays, which are likely to have become a modern replacement for the television and are unlikely to cost any more than an average television does today. The technology will become an essential tool 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 simple tasks to shopping around for the best prices to complex financial decision-making.

Therefore, visualization should exploit the experience gained over the last two decades in VR research, often ignored in the media, while continue to pursue the application of the ever-evolving VR technology in visualization systems. Moreover, visualization researchers should not treat immersive worlds only as presentation mediums but as sources of data, especially when it comes to interaction, collaboration and sense of presence.

Towards a Mixed Reality

An even more interesting prospect, different from the exclusivity that a VR environment entails, is that of a Mixed Reality (MR) (see inset on Mixed Reality Continuum). In MR the informational content is presented in a synthetic world where computer-generated and physical objects co-exist. This concept somewhat extends ubiquitous computing, often regarded as the antithesis of VR.[21] In fact, MR enhances our physical world in numerous, subtle and often invisible ways.[22] Contrary to fully immersing a user in a computer-generated world as VR does, or embedding physical computational entities in our environment, as ubiquitous computing does, we can fuse these paradigms and enhance our physical environment with both physical and virtual artifacts simultaneously. These artifacts are not necessarily visible but are perceivable, much like 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 are therefore immersed in an informational space that can extend beyond our immediate physical world, while providing context aware information and allowing interaction in a natural, fluid, way.

Barba et al.[21] argue that MR research, which at the moment is mainly driven from the paradigm's relationship with smartphones, needs to focus on all aspects of human cognition and not just vision, as it has been done for the past two decades or so. They further add that MR space (physical or synthetic) acquires meaning, through context and that different technologies, and their quality has a direct impact on the interaction capabilities.

This expanded version of *perceptualization* is intrinsic to the future manifestation of visualization. It is safe to 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 will slowly enhance our world, much like Vernon Vinge describes in Rainbows End,[25] we expect to see MR systems encompassing different modalities and fluid interfaces, be accessible in the environment through physical and synthetic display and interaction mechanisms, as well as wearable devices, like the Google Glass HMD. Moreover, novel types of natural interactions are becoming more widespread. Affective computing[23] (computers that respond to emotion) that uses different types of modalities, such as Electroencephalography (EEG) to record electrical signals from the brain, can be used to control different devices and potentially change the way visual depictions are displayed, or respond to user input.[24]

Conclusions

As the trend for using visualization technology starts to become part of our everyday lifestyle for communication, productivity and entertainment we forsee that the rate of adoption for novel interaction technologies will increase. The higher demand for technology can be expected not only to lead to cheaper production costs, but also a wider range of competition as new technology is developed and new manufacturers get involved, leading to much cheaper products to the end user.

We live in an exciting time for human-computer interaction research. New input and output modalities that are starting to appear provide intriguing new ways to interact with computers and offer new opportunities and challenges for visualization.

In this article, we have attempted to classify and categorize this new breed of devices to point to the new possibilities that they enable. However, these new devices are just tools, and the responsibility of *how* to use them to best effect lies in our hands—those of visualization researchers, designers, and practitioners worldwide.

Acknowledgments

This work was initiated from the Schloss Dagstuhl seminar on information visualization (10241), and the authors wish to thank A. Kerren, C. Plaisant, and J. T. Stasko for their help and encouragement. This work is partially funded by the European Commission through project EVIVA, 531140-LLP-1-2012-1-UK-KA3-KA3MP in the Lifelong Learning Programme.

References

1. T. A. DeFanti and M. D. Brown, "Visualization in scientific computing," *Advances in Computers*, vol. 33, no. 1, pp. 247–305, 1991.
2. M. Ward, G. Grinstein, and D. Keim, *Interactive data visualization: foundations, techniques, and applications*. AK Peters, Ltd., 2010.
3. R. Spence, *Information Visualization: Design for Interaction*. Pearson Education, 2007.
4. M. Weiser, "The computer for the 21st century," *Scientific american*, vol. 265, no. 3, pp. 94–104, 1991.
5. N. Elmqvist and P. Irani, "Ubiquitous analytics: Interacting with big data anywhere, anytime," *IEEE Computer*, vol. 46, no. 4, pp. 86–89, 2013.
6. S. Oviatt, R. Coulston, and R. Lunsford, "When do we interact multimodally?: Cognitive load and multimodal communication patterns," in *Proceedings of the 6th International Conference on Multimodal Interfaces*, ser. ICMI '04. New York, NY, USA: ACM, 2004, pp. 129–136.
7. S. Oviatt and P. Cohen, "Multimodal interfaces that process what comes naturally," *Communications of the ACM*, vol. 43, no. 3, pp. 45–53, Mar. 2000.
8. S. A. Panëels and J. C. Roberts, "Review of designs for haptic data visualization," *IEEE Transactions on Haptics*, vol. 3, no. 2, pp. 119–137, 2010.
9. E. T. Hall, *The Hidden Dimension*. Garden City, NY: Anchor Books, 1966.
10. S. Greenberg, N. Marquardt, T. Ballendat, R. Diaz-Marino, and M. Wang, "Proxemic interactions: the new ubicomp?" *Interactions*, vol. 18, no. 1, pp. 42–50, 2011.
11. M. R. Jakobsen, Y. Sahlemariam Haile, S. Knudsen, and K. Hornbæk, "Information visualization and proxemics: design opportunities and empirical findings," *IEEE Transactions on Visualization and Computer Graphics*, vol. 19, no. 12, pp. 2386–2395, 2013.
12. Z. Pousman, J. T. Stasko, and M. Mateas, "Casual information visualization: Depictions of data in everyday life," *IEEE Transactions on Visualization and Computer Graphics*, vol. 13, no. 6, pp. 1145–1152, 2007.
13. P. Dourish and G. Bell, *Divining a Digital Future - Mess and Mythology in Ubiquitous Computing*. MIT Press, 2011.
14. P. Isenberg, N. Elmqvist, J. Scholtz, D. Cernea, K.-L. Ma, and H. Hagen, "Collaborative visualization: definition, challenges, and research agenda," *Information Visualization*, vol. 10, no. 4, pp. 310–326, 2011.
15. C. Harrison, "Appropriated interaction surfaces," *IEEE Computer*, vol. 43, no. 6, pp. 86–89, 2010.
16. L. Chittaro, "Visualizing information on mobile devices," *Computer*, vol. 39, no. 3, pp. 40–45, 2006.
17. G. Çetin, R. Bedi, and S. Sandler, Eds., *Multitouch Technologies*. NUI Group, 2009, online book - http://www.nuigroup.com/.
18. K. Kim, W. Javed, C. Williams, N. Elmqvist, and P. Irani, "Hugin: A framework for awareness and coordination in mixed-presence collaborative information visualization," in *Proceedings of the ACM Conference on Interactive Tabletops and Surfaces*, 2010, pp. 231–240.
19. J. C. Roberts and R. Walker, "Using all our senses: the need for a unified theoretical approach to multi-sensory information visualization," in *IEEE VisWeek 2010*, ser. Workshop on The Role of Theory in Information Visualization, R. Kosara, T. J. Jankun-Kelly, and C. Weaver, Eds., 2010.
20. D. A. Norman, *Things that Make Us Smart: Defending Human Attributes in the Age of the Machine*. Addison-Wesley, 1994, ch. Visual Representations.
21. E. Barba, B. MacIntyre, and E. Mynatt, "Here we are! where are we? locating mixed reality in the age of the smartphone," *Proceedings of the IEEE*, vol. 100, no. 4, pp. 929–936, April 2012.
22. W. E. Mackay, "Augmented reality: linking real and virtual worlds: a new paradigm for interacting with computers," in *Proceedings of the working conference on Advanced visual interfaces*. ACM, 1998, pp. 13–21.
23. R. W. Picard and J. Klein, "Computers that recognise and respond to user emotion: theoretical and practical implications," *Interacting with computers*, vol. 14, no. 2, pp. 141–169, 2002.
24. D. Cernea, C. Weber, A. Ebert, and A. Kerren, "Emotion scents: a method of representing user emotions on gui widgets," in *IS&T/SPIE Electronic Imaging*. International Society for Optics and Photonics, 2013, pp. 86 540F–86 540F.
25. V. Vinge, *Rainbows end*. Pan Macmillan, 2011.