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CHAPTER 9

Reflections on Ubiquitous Visualization

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CONTENTS

There is a growing demand for data visualization on mobile devices in order to facilitate exploration of locally-relevant data on-the-go. In this chapter, we provide an outlook into the future of mobile visualization which we anticipate will see a growing emphasis on *ubiquitous visualization*. We provide an overview of research in ubiquitous data visualization by interviewing four renowned researchers who have explored data visualization in novel settings with new modalities and technologies that go beyond mobile devices. We report on our discussions and distill important themes and their visions for the future of ubiquitous data visualization. We discuss envisioning scenarios for this emerging research area and reflect on its specific dimensions going beyond mobile data visualization.

9.1 INTRODUCTION AND CONTEXT

This concluding book chapter sets out our vision for moving toward a fuller understanding of *ubiquitous visualization*. While mobile visualizations might connote visual tools for sense-making on small mobile displays, we envision that these mobile visualizations will increasingly move towards ubiquitous visualization: visualization that is available to people everywhere and at any time. The natural leap from mobile to ubiquitous visualization is motivated by the pervasive nature of displays, the ready availability of cloud data, and the growing emergence of displays embedded in our environment. Current mobile visualizations imply having a personal mobile device, such as a smartphone or smartwatch. But as discussed in the previous chapters, some of the limitations of these form-factors such as small display size as well as limited input mechanisms hinder the vast range of applications and scenarios one can imagine when visualizations are ubiquitously accessible. Furthermore, emerging devices including head-worn, flexible or textile displays warrant renewed consideration for how these might be employed for giving access to information displays, at any time and at any place. While mobile devices in current form factors may still form an important part of ubiquitous visualization as a way to have personal rather than shared views, we will increasingly see a variety of different form factors and the wider integration of visualizations in the environment.

Researchers have been envisioning new directions for visualization beyond the desktop [70], leading to the idea of visual analytics everywhere or ubiquitous analytics [26]. Related visions that expand on this include situated and embedded visualizations [51, 62, 97, 99] and immersive analytics [61]. Early prototypes of systems motivated by these new directions have been made possible through the accelerating deployment of novel technologies many of which are becoming consumer ready products. Devices with pervasive displays are no longer necessarily rectilinear and can be free-form [82], dynamically assume a required shape [1], or dissolve into Augmented Reality projections [66, 15]. Furthermore, as users equip themselves with more than one mobile device, opportunities for cross-device visualization create new design opportunities for multi-user and group-based sense-making activities [7]. In addition to enhanced display power, we are also seeing a revitalization and application of multi-sensory input capabilities [60], beyond singular devices, such as a cursor or touch input on smartphones, to include proxemics [4, 24, 44], spatial tangible interaction [55, 59], gaze-input [85], as well as speech [36, 37, 83] for visual sense-making.

While we envision a growing future emphasis on ubiquitous visualization, it is important to acknowledge that much of the early work into what can be considered ubiquitous visualization took place decades ago, even before smartphones became a commodity. Research into *ambient displays* and *calm computing* was motivated by exploring ways to present and visualize contextually-relevant information in the periphery of attention, with the goal of informing people without overwhelming them [92]. Examples include Natalie Jeremijenko's Live Wire [92] (essentially a self-actuated data physicalization [45] of network traffic), the ambient displays developed at the MIT Tangible Media group [100], Information Perculator [38], Tollmar's virtually living together lamp [87], Ambient Devices, Inc.'s Ambient Umbrella [69], Data Fountain [88], and the Power-Aware Cord [33]. Indeed, one might argue that we have come full circle with recent research into ubiquitous visualization returning to the guiding forces behind this early work in the ubiquitous computing community. From the earliest demonstrations of calm computing or ambient displays to the ever growing presence of dot lights in our environment [35] or the potential of future output technologies such as flying displays [17, 81, 101], we cannot overlook the possibility that mobile visualizations might meld and become part of our surroundings. Purposefully and quietly, yet pervasively accessible due to the availability of cloud data, such displays will play a critical role in our every day decision making. Yet despite these advances we still question how best to move forward to realize these visionary proposals? What challenges are we faced with in the process? What has been done, what is next, and what research challenges remain?

This chapter takes a first step towards answering these questions. Unlike methods used for developing content for the previous chapters, we, the authors of this chapter, took a different approach. We first identified papers that have in one way or another broached on the topic of ubiquitous visualization, some of which were cited above. While the authors of these papers did not necessarily explicitly label their work as "ubiquitous visualization", they envisioned many of the prospects supported by this chapter's theme. We decided to interview one author from each of the papers in this initial collection to obtain a handle for how such emerging technologies have impacted their envisioned ideas. The interviews were composed of questions on a general nature about the theme, but also of more specific questions about concepts that the authors alluded to in their work.

While undergoing developments on mobile visualization are still nascent, our interviews enabled us to identify recurrent themes and challenges to be tackled in future research. First, we briefly summarize our approach (Section 9.2). Next, we present the individual interviews with each of the four researchers in detail, covering a common set of questions, and highlighting particular aspects of their relevant and important publications in this area (Sections 9.3, 9.4, 9.6, 9.5). This is followed by reflecting and discussing overarching and important themes we identified across the interviews (Section 9.7). To better highlight our envisioned future, we provide an overview of possible application scenarios including those that our interviewees highlighted as having much potential for ubiquitous visualization (Section 9.8). Finally, we revisit the dimensions of mobile data visualization from Chapter 1, and discuss how well the vision of ubiquitous visualization is covered by these dimensions (Section 1.2).

9.2 APPROACH

To understand where mobile visualization is heading next, and the opportunities, challenges, and research potential in fusing into ubiquitous visualization, we interviewed four prominent researchers,[1] known for their research in mobile visualization and their vision for new ubiquitous, situated, and mixed reality technologies:

- Wesley Willett, Associate Professor at the University of Calgary, Canada
- Niklas Elmqvist, Professor at the University of Maryland, United States of America
- Sean White, at the time of our interview: Chief of Research & Development at Mozilla, United States of America
- Yvonne Rogers, Professor at University College London, United Kingdom

Two to three authors of this chapter conducted semi-structured interviews with each of our interviewees over videoconferencing. One author led the interview, while one or two other authors took notes. Each interview lasted about an hour and consisted of a set of generic questions, common to all interviews, followed by a set of specific questions that were inspired by how the interviewees' research relates to mobile and ubiquitous data visualization. Interviewees were provided with the questions in advance. Interviews were recorded and transcribed in full.

In the following sections, we describe the relevant background of each interviewee, followed by the outcomes of their interview, structured along the set of generic and specific questions. We decided not to use a coding approach to find commonalities and trends in the interview data. We chose to summarize each interview in full, to present the variety of individual perspectives of each of the interviewees. Each interview consists of editorial summaries interspersed with quotes from the interviewee.

[1] *Headshots of all interviewees in this chapter courtesy and © of the respective interviewee.*

9.3 WESLEY WILLETT ON EMBEDDED DATA REPRESENTATIONS

Wesley Willett is an Associate Professor of Computer Science at the University of Calgary where he holds a Canada Research Chair in Visual Analytics and leads the Data Experience Lab. His research interests span information visualization, social computing, new media, and human-computer interaction, and his research focuses on pairing data and interactivity to support collaboration, learning, and discovery.

A notable contribution of Willett's that is of key relevance to this book chapter is his 2017 article on "Embedded Data Representations" [99], co-authored with Yvonne Jansen and Pierre Dragicevic. In this paper, Willett and colleagues contribute a conceptual framework and foundation for thinking about visualizations that are connected to the world in which they are situated. They formalize the notion of physical data referents, or "physical spaces, objects and entities that the data refers to." For example, physical data referents could be the houses that the data in a real estate data set refers to, or the employees described in a company directory. Willett et al. distinguish between visualizations or physicalizations that are either *situated* or *embedded*, where the former display data in proximity to physical data referents and the latter display data so that it coincides with the physical data referent.

What does mobile visualization mean to you? How do you see it being used today?

Willett notes that the term *mobile visualization* has felt a little confusing in the last couple of years. "When I tend to use the term 'mobile', I am mostly thinking about the form factor of the devices. What it suggests to me is visualization on watches, phones, and tablets. And that's distinct from other terms like ubiquitous visualization and immersive analytics." On how he sees mobile visualization being used today, Willett replies: "If I had to characterize things that I see as mobile visualization right now, it's things like Fitbit tracking, or health data being shown on Apple watches." He then notes that with other things that are more about a vision for visualization in other environments, his tendency has been to use other terms such as ubiquitous visualization or immersive analytics.

What do you see as the benefits of the visualization being mobile?

"From a practical standpoint, mobile visualizations are more accessible by virtue of being on these other hardware platforms. So, in some cases, it's easier for mobile visualizations to be visible in places where people can take action based on them or where they are situated with respect to an appropriate task. There are also a lot of cases where people are creating visualizations on mobile devices just because this is a more convenient software platform."

Continuing on this, Willett points out that with a lot of the current examples of mobile visualizations, it's much more about making the data available in a mobile setting, but "it doesn't necessarily make them inherently more situated with respect to the tasks that they are designed to support." He sees the current generation of mobile visualizations as being more about the fact that "these hardware platforms are with us all the time, rather than doing anything that is really context-aware or embedded in a particular task or application."

How do you envision mobile visualization contextually adapting to aid a user's activity?

Willett says this is the space that he is most interested in: "Thinking about how you can start to embed visualizations into the spaces, and tasks, and even objects or environments where people are actually performing tasks. By connecting visualizations to spaces, we can provide access to data in ways that support specific tasks, and in a way that is very timely and is very situated, helping people experience data in a way that supports decision-making and stimulates reflection." He has mostly thought about this in the context of *personal informatics*, but he also sees much potential in other domains, such as: "Specific tasks in construction or maintenance, where there are clear direct applications of data to measurable tasks that are easy to design around." Willett mentions that embedding data in specialized or everyday tasks is very compelling, but that there is still lots of work to do.

What different application areas and target user groups do you envision in the future for the consumption of data on mobile devices (versus visualizations on the desktop)?

One place where we already have a lot of visualizations that are deeply embedded in the task at hand, according to Willett, is in driving: "Our cars are actually full of little relevant visualizations that are providing specific pieces of data about our current environments and are directly translating into how we drive." Willett explains that we might see many other kinds of operations or settings with that same level of augmentation. Examples include performing surgery or maintenance, brushing your teeth, or making coffee: "These are all tasks where you might be able to bring data to bear in a way that is either interesting personally or allows you to do the task better. And the integration of these visualizations with the tools and the environments could look a lot like the growing integration of visualization into cars." Willett then mentions the example of the large display in a Tesla, and all of the different kinds of information the driver has at their disposal. Rather than just showing speed or RPMs, the display also shows the driver a model of the environment, including the position of nearby vehicles and the current speed limit — things they cannot perceive with their own eyes. Willett explains: "There are many kinds of data that those displays are providing that are incredibly contextually relevant to the task of driving and they're presenting that data via visualizations. I suspect that integrating these kinds of task-specific visualizations into a variety of other contexts could be a really big opportunity for the field." He discusses how this is very much in line with the traditional benefits of visualization (augmenting perception, supporting visual computation, augmenting memory), but doing all of this "in a way that is very grounded in particular spaces, or tasks or tools."

What is the current big thing for mobile visualization? And what do you think will be next?

Willett notes that while Augmented Reality (AR) and Mixed Reality (MR) are currently getting a lot of attention, lots of challenges remain. The more he worked in this space, the less he's convinced that AR or MR is the way forward, at least in many situations. Instead, he thinks screens may be more useful in the short term: "We're thinking about scenarios in which people are using many devices with attached displays, or have many displays that are integrated into their environment. The car analogy actually works really well with this too — the technology that is enabling the tighter and tighter integration of visualizations into cars is still screens, but it is screens embedded in the right places." Willett explains that he feels that integrating visualizations in everyday spaces using projection and displays is more promising in the near term than AR and MR because it avoids many challenges that these technologies present: "And it means that the visualizations become shared objects that people are able to socialize around and examine together. It's also easy to integrate small displays into many existing settings in a way that is technically not that easy for lots of current generation AR tools."

We then mention the LED displays that are integrated in the sidewalks to indicate the green wave on the bicycle paths in Copenhagen[2]. They give cyclists an indication of whether they need to speed up or slow down to go 20 km/h and catch the wave of green traffic lights, requiring no instrumentation. Willett notes: "Exactly. I think that's a really nice example of simple embedded displays. In a lot of cases, the goal of these new visualizations can be really subtle — not providing strictly analytic views, but instead surfacing data in environments in ways that allow people to make good decisions or perform tasks better."

How do you see mobile visualization transitioning to ubiquitous visualization?

"The end goal as I would frame it is: having access to data where and when it's useful." Willett notes that visions of ubiquitous visualization such as ubiquitous analytics [26], are more satisfying to him if they are technology-agnostic. He notes that to make data available in places so that having access to it changes the way you make decisions, there are many design and technology factors to consider: "What is available? What is reliable? What is acceptable from a social perspective? [...] My hope is that designers increasingly have access to a variety of different technologies for creating visualizations that live beyond the desktop, and that designers in this space can now focus on creating visualizations that are nicely tailored to real tasks, rather than focusing on particular hardware platforms just because those platforms are the current sexy thing." Looking ahead, Willett notes: "I can imagine twenty or thirty years in the future where everyone has a little display that is projecting into their retina and all of them are perfectly synchronized. Something like retinal displays could become the de facto technology for visualization if it's ultimately cheaper, easier, and more accessible than

[2]Streetfilms Snippets – Green Wave LED Lights (Copenhagen, Denmark): https://www.youtube.com/watch?v=6Kx1XZeFkXk

doing something that's physically instantiated in the real world. And that's still an interesting thought experiment for visualization researchers to consider. [. . .] However, from a practical perspective, there may be lots of other current technologies that we can use to achieve a lot of the same ends."

How does your framework for situated and embedded data representations relate to mobile data visualization? And to the related visions of ubiquitous analytics or immersive analytics?

"So I think of all of these as operating on slightly different levels. I tend to think of the term mobile visualization as a more restrictive concept that is talking specifically about particular hardware platforms. I think of ubiquitous analytics as a broader vision for the integration of data and visualization into a wider range of contexts. Within those, the notion of situated and embedded data representations is more of a tool or framework that lets you think critically about a few specific aspects of these visualizations."

Willett mentions that he sees *situated* and *embedded* as language that facilitates discussing and reasoning about specific design decisions for visualizations that might span a number of different platforms and visions. He notes that it is useful to describe what is different about them, particularly in terms of spatial or temporal indirection. When we asked whether he sees his framework as a conceptual framework to aid design, he answered: "Exactly. The language of situatedness and embeddedness and the discussions that led to that terminology were extremely helpful for me. I think this language helps unpack some of the trade-offs that make visualizations that are connected to the physical world more or less useful and makes it easier to extrapolate from current systems to imagine future designs. This terminology has grounded the majority of the conversations I have had about these kinds of visualizations in the last couple of years."

What propelled the idea of producing a unifying framework for what others may have termed as Situated Analytics or along the lines of ideas proposed by White & Feiner?

"Our paper originated from discussions about a whole bunch of existing visualization systems, including White & Feiner's, that were somehow connected to the physical world. We also considered possible future visualizations inspired by the "Death of the Desktop" workshop at IEEE VIS in 2014 [46]. For example, my submission to that workshop was this "artefact from the future" that imagined visualizations made up of swarms of tiny drones. We ended up using completely different language for it first, like *physically embedded visualizations*, but ultimately preferred language that aligned with some of the earlier literature."

Willett mentions that they were at that time looking at several other related framings, including Dietmar Offenhuber's indexical visualization processes [65] (and subsequent work on autographic visualizations [64]). Willett and his co-authors tried to reason about the differences between the examples to give themselves a language for explaining the differences. Willett continues: "And, that's part of what ended up connecting it back to White & Feiner's work [93] and the work on situated analytics

[26]. It was clear that people were using similar terms but using them to talk about systems that are qualitatively somewhat different."

In your paper, you mention that there is still little empirical evidence for the benefits of situated/embedded visualizations. Since writing the paper, have you been able to identify new insights or evidence for either benefits or drawbacks of these approaches?

"The automobile example is one that I think has become more clear to me in the last couple of years, especially as we've seen new in-dash visualizations that include much more data and are intending drivers to use that data to make driving decisions. I think this is one of the most compelling, real-world, widely deployed evidence for the utility of situated visualization. In my own work, we also thought a lot more about this in the context of personal informatics. That research has felt very satisfying to me, because part of the work has involved building and then personally using lots of new visualizations for self-tracking. [. . .] This includes a bunch of situated visualizations which I continue to use around the house as part of my daily routine. I feel they aid my ability to reflect, and to do so in everyday settings. That suggests to me that having access to right data can be helpful in lots of domestic settings where we don't tend to think of visualization that much. Our recent work on situating visualizations in the context of construction and maintenance also makes me think that there is a lot of value to be gained by surfacing data in-context for those tasks. At this point, I haven't seen many quantitative studies that have tried to really make the case for the benefits of situated visualizations. However, that's something that we would still benefit from as a community, if only to be able to more concretely articulate their benefits. At least qualitatively, I feel now I have a lot of examples that make a strong case for the approach."

How dependent are embedded visualizations on Augmented Reality (AR), Virtual Reality (VR) or Mixed Reality (MR) technologies? Do you envision other forms of display/interaction techniques being more appropriate for embedded visualizations than the current state-of-the-art in AR/VR/MR hardware/techniques?

"So I think that AR/MR is an interesting technology stack to build these on, and there are a variety of settings and visualization designs that could be difficult to implement using physical displays. On the other hand, I still think the affordances of situating visualizations in physical ways are interesting. In the original VIS paper, we even talk about examples of embedded physicalizations like actuated store shelves that would move in response to sales data. The drone swarm example that motivated a lot of our discussions is another example of how you might create visualizations using technologies that provide more than just a virtual overlay and are instead physically integrated into the space." Willett explains that this has interesting implications for how one might interact with it. For example, is there co-location between sensors or displays, can it actively manipulate the environment? While these questions come up when thinking about technologies that are not AR, Willett notes that for many of these scenarios, this can still be done using an AR overlay as well.

We elaborated on this by referring to modern parking garages where you have

LEDs over the parking spaces that show which spots are free as an example that does not rely on AR or MR. Willett replies: "Yes, I think parking indicators are another really interesting example that has emerged in a widespread way in the last five years or so. Every time I see it, I think, oh yeah, that's a great example of an embedded visualization that is quite useful, while also being relatively low-tech. It is really just a simple sensor and one bit of output that are co-located in a space, and then multiplexed through the entire environment so it allows you to make decisions."

What is your perspective on the information density that would be typical for situated and embedded visualizations? Would one typically use glanceable visualizations with very few data attributes, or can you also envision situated or embedded visualizations that present a large amount of data?

"My intuition is that this is a design problem that anyone who is trying to surface information in spaces has to deal with. Any visualization design needs to consider who the viewer is, what the data is, and what the task is. I think that if you have the potential to display information everywhere, then by definition you have to start to make decisions about information density and about attention. That probably suggests that if you are displaying an embedded visualization that covers your whole field of view or appears in many places in the environments, you're likely to want to simplify it or provide more glanceable overviews."

Willett adds that information density isn't the real problem, it's complexity: "If you had an AR overlay showing dense, pixel-level temperature readings for the entire space, that still actually might be fine, depending on the task. It's high-density, but low complexity. But if I have very complicated data that's difficult to visually parse overlaid all over my entire field of view, then that seems likely to be problematic. I think that all visualizations pose problems for attention and that, especially if you're designing systems that can encompass your whole view or can introduce many visualizations at the same time, you're going to have to make decisions. Which visualizations are visible at any given time? How visually salient are they? How do you transition between them?"

You say it also depends on the task and the activities that people are engaged in. In applications for construction or maintenance, maybe in those situations you do actually want to delve into why this machine is not performing as expected, see different charts and explore this in more detail?

"Exactly. The challenge is thinking about how you surface that information, maybe in a staged way. If I am walking into a space with many different pieces of equipment, all of which could potentially have a problem, maybe I need some sort of higher-level glanceable view. Once I've identified the one that is the likely cause of the problem, then I might want to start to pull up more detailed visualizations that highlight particular aspects of that machine and overlay a lot of additional data specific to it. You can think about handling those transitions in many different ways including ones that are driven by locomotion and incorporate notions of proxemics."

While "data" has a big role in embedded visualization, what is the role of people and locations?

"I think that people are, at the end of the day, the most important piece of this. If you have the ability to display lots of data in lots of ways, all over the environment, then at the end of the day, you need to be designing the visualizations in a way that reflects the people that are going to be using them and the tasks that they are going to be performing. The designs need to be tailored to those task and try to help manage people's attention and improve their ability to make sense of that data."

Embedded visualizations seems to be a way to describe and compare different kinds of data representations related to the physical world? Are there other purposes for embedded visualization?

"I think of it in terms of frameworks generally. These kinds of frameworks are useful because they allow us to describe and compare both existing systems and future possible systems. They also make it easier for us to identify points in the design space that haven't been explored. The things that I find most helpful about this framework is that it's given us the ability to discuss the differences between visualizations that are just situated versus ones that are embedded and to think about the level of indirection in those embeddings. This language has shown up in almost every discussion around a visualization system that I have had since, and has been extremely useful." Willett argues that there are still opportunities to expand the framework further in terms of temporal indirection (which was only briefly touched upon in their paper) or semantic indirection, i.e., how compatible the visualization is with the task.

In terms of temporal indirection, we discuss an example where it would be possible to show for a certain location how many cars passed by 30–40 years ago compared to now. Willett replies: "Yes, I think this temporal indirection as a space is ripe for further unpacking. You can consider not only temporal indirection but also temporal aggregation, and also the liveliness of the data. Am I looking at data where I can reach out, make a change to the environment, and now the visualization will change based on that? Am I looking at data that is historical? Am I looking at data that is live but that actually I can't impact? I think that there is still a rich design space here that would be worth providing some more language for."

Is there a kind of "data-oriented proxemics" with Embedded Data Representations?

One of the interviewers seemed to remember that Willett's embedded data representations work [99] quoted Waldo Tobler's first law of geography – "Everything is related to everything else, but near things are more related than distant things.". We mentioned this and noted that it reminded us of theories of and work on proxemics in HCI where the relationships, including even how people face one another, is important for their interactions (e.g. Hall's proxemic zones [34], F-formations [19, 52]). We asked Willett if embedded data representations naturally imply a data-oriented version of existing HCI work in interaction using proxemics [32]:

"I don't know that we ever quote Tobler's law in the paper, but it is something that showed up in some of the presentations that we have given about the work. In hindsight, I think Tobler's law is one of these oft-repeated statements that almost feels like a truism, and I'm not quite sure that it applies neatly here. But I do think that the notion of proxemics and proxemic frameworks map themselves nicely to any discussions around ubiquitous analytics and are definitely compatible with the situated/embedded framing. I think that human spatial perception provides a lot of nice opportunities for using location and attention information to determine which visualizations are shown or what data density you're using. There's definitely a very natural relationship to existing work around proxemics."

To follow up, we asked whether early work in this area such as Vogel & Balakrishnan's work on interactive public ambient displays [89] may be a good match, as well as Isenberg et al.'s work on hybrid-image visualization [43] (of which Willett was also a co-author): "Totally. My sense is that if you look back at the history of proxemics systems, many of the classic examples are data-driven, even if they are not necessarily complex analytic visualizations. I think that when designing visualizations for real environments, using information about where the people are and where their attention is directed to adapt things like the level of detail makes a ton of sense. It would be interesting to think about trying to draw attention to the proxemics literature for the visualization community. Because I don't know how much overlap there is between proxemics researchers and the people working in ubiquitous analytics or situated analytics. My sense is that the overlap might not be huge."

Any final comments or things to add?

"The one other thing I will add, is that I would love to see more work on design futuring in the visualization community. The "Death of the Desktop" workshop at VIS in 2014 was one of the most inspiring sessions that I've been a part of in my entire history in the community. It inspired much of my research and teaching over the past half-decade and left me convinced that these opportunities to actually create artifacts from the future and do design futuring for vis are really fruitful." Concluding our interview, we note that it may be worth organizing a similar provocative design futuring session on the "Death of Mobile."

9.4 NIKLAS ELMQVIST ON UBIQUITOUS ANALYTICS

Niklas Elmqvist is a full professor in the iSchool (College of Information Studies) and Director of the HCIL (Human-Computer Interaction Lab) at the University of Maryland, College Park. His research areas are information visualization, human-computer interaction (often applied to visualization problems), and visual analytics. In much of his research, Elmqvist is concerned with investigating the potential of novel computing environments and styles of interaction for data visualization and analysis purposes, including research on software infrastructures required to support the engineering of these new visualization environments.

Among Elmqvist's notable contributions in the context of this book chapter are his co-authored IEEE Computer Graphics and Applications article "Visualization beyond the Desktop" [70] and his article on "Ubiquitous Analytics" [26], co-authored by Pourang Irani. These articles propose research on visualizations beyond the desktop and *Ubilytics* as situated sensemaking of big data anywhere and anytime, where the analytical process is embedded into the physical environment. This allows analysts to interact with complex data in their offices or in-the-wild, individually or collaboratively, synchronously or not. All of these aspects of Niklas Elmqvist's research and work, i.e., visualization beyond the desktop, ubiquitous analytics, and the engineering of visualizations are reflected in his interview, which is summarized in the following.

What does mobile visualization mean to you? How do you see it being used today?

Elmqvist answers this introductory question: "Data visualization is not designed for specifically sitting in an office, maybe I'd even go further, so not using a personal computer, almost anything that is not using a personal computer, but probably focused on situations where you're on the go, rather than in a fixed setting." He remembers a keynote given by his colleague David Ebert at the Graphics Interface conference in 2008, which was entitled "Mobiquitous Graphics and Visualization". Elmqvist notices that not much mobile visualizations have been developed since then: "We have seen research papers . . . , but I don't see there being significant commercial applications with visualizations in the field."

What do you see as the benefits of the visualization being mobile?

Since mobile devices become our personal computers with high screen resolution and a lot of processing power, what sets them apart might be the mobile usage itself. Elmqvist mentions "so what makes the difference is the context of use. And of course, if I am just walking around and looking at sales data, the boundary between a personal computer and a tablet or smartphone in particular is being erased almost entirely, because they are converging. But, if you truly want to take advantage of the fact that you are mobile, then you want to take advantage of some type of context-aware information where you are. [...] Finally, that killer app where you use the location of where the person is in the world is not trivial. It is what makes the difference between a mobile and a normal visualization. But it has to be a form of sense-making that is in-situ, and if you take advantage of location information, and it should somehow uniquely make it easier for you to make opportunistic or serendipitous decisions or analyses that you would need more time or effort to do offline, ex-situ, in an office."

How do you envision mobile visualization contextually adapting to aid a user's activity?

It is an interesting aspect that people do not just look at the data while on-the-go, but the context allows them to discover something completely new or to get some suggestion. Elmqvist reflects: "There is lots and lots of data being collected about the world, especially about cyber-physical systems, things that exist both in the real world and in the digital world. [...] The problem is, the internet, for all its advantages, has the disadvantage that it 'throws away' the real space. There is typically no relation to the real space."

Elmqvist recalls William Gibson's "Neuromancer" novel, where he talks about cyberspace. "It is like a virtual version of the real world. So, everything in the real world has a virtual representation. So that aspect is of course lost in the internet of today. But I think we want to bring back some of it, where the data that is being collected from the real world should be brought back as digital data in the real world, that you can access using a mobile device, some mobile visualization."

He further elaborates on a project turning the University of Maryland campus into a testbed for situated data, where a multitude of information reaching from bus schedules over crime data and safety recommendations up to information about historical buildings is being accessible via smartphone or AR goggles. "Basically, it is about the notion of a real place as an index into the digital world. That is one of the potentials of mobile visualization that it really takes advantage of your spatial location. And that can make decisions easier with less effort. [...]"

What is the current big thing for mobile visualization? And what do you think will be next?

Responding to this question, Elmqvist primarily refers to personal information and emphasizes its big potential. "You tend to see them in things like a smartwatch that captures and displays data. And of course, if you have a Fitbit app or Apple health app that lets you track these information. I think this is certainly a big thing, because it has a personal connection and can make people relate to the data better."

In his NSF project Data World, it is all about personal, recreational use. "So we haven't really looked at professional settings, but my colleague Amitabh Varshney runs the Augmentarium here at UMD, which is all about creating AR experiences. His goals are mostly professional, so that is things like a surgeon wearing AR goggles and they get a visualization of the patient's CAT-scans superimposed on their bodies, or its supporting soldiers in a battlefield [...]. I don't know what the big thing is.

My view is mostly on a personal information space, but I think there's significant potential for applying this to professional settings, too."

How do you see mobile visualization transitioning to ubiquitous visualization?

We then discussed that this usage of mobile visualization in rather professional domains would be a first aspect of that expansion of today's mobile visualizations into future ubiquitous visualizations. Second, it would be to make visualizations far more contextual, to integrate them into real-world contexts. And a third interesting aspect are AR goggles or other augmentation technologies that might play an increasing role in the future. Asked about these potential ingredients on the path to ubiquitous visualization, Elmqvist responded:

"I agree. I think that's the case. I am not one to tell you whether and when AR will actually have a breakthrough, because we as computer scientists have been burned too many times by VR and how hard that has been to get it off the ground. AR is promising, but AR glasses will not be worn by everyone. I think there is a big gap to actually reach that stage. But, having said that, I think of Pokémon Go, that is a good example of integrating the virtual world with the real world. There is much potential for creating these ubiquitous visualization experiences using existing devices that we have. You don't have to invest in huge computer infrastructure, since people already have lots and lots of exciting devices in their pockets."

Which role will Mixed Reality technologies play in the future? What could be alternatives or other enabling technologies?

In this part of the interview, Elmqvist further elaborates on what he calls *ubiquitous visual computing*: "Something that I realized several years ago came from reading Dourish's and Bell's book 'Divining a Digital Future: Mess and Mythology in Ubiquitous Computing'. The whole message of that book is that ubiquitous computing is already here, [...] the notion of ubiquitous computing that Mark Weiser proposed in the 1990s actually has been reached already. It's just that it is a moving target. People tend to think, it is the future. But, if you look at what we have in our pockets and the computing infrastructure we surround ourselves with, it really is the vision that was originally proposed. Yes, the devices are not entirely invisible, and they actually still have displays, [...] they have not disappeared. But, I think that actually points to the notion of not just ubiquitous computing, but *ubiquitous visual computing*.

He argues that instead of thinking 20 years ahead and believing that in 20 years we are all going to wear AR goggles and have clothing that measures everything and speaks to us, we should rather "take advantage of what is already here and open our eyes and realize that there are lots and lots of devices already that we can use to realize this vision of ubiquitous visualization, ubiquitous visual computing, all the pixels that we could be using. That's what I try to do based on my work and based on my ideas of ubiquitous computing."

Some people argue that in the future people do no longer wear bulky AR goggles, but perhaps retina displays or implants reading and producing brain signals. We therefore asked Elmqvist, whether he believes that we still need external displays within the environment or people's hands. "I am a realist and a pragmatist. So that's why I have not considered much of those future devices, I have been focusing on the ones that we have, but you're right, if, for example, you have an AR display or seamless one where you can just put it on the retina [...] there is clearly no need to put any physical displays in our world, as you could 'fake' them. Of course, that would be a game changer."

Elmqvist also referred to the 'Silent Augmented Reality' blog by Dominikus Baur [10], where he described a dystopian vision of advertisements flashing everywhere into people's faces. "If you want visualizations, data and displays available everywhere you need to find a way to not pollute people's virtual space, because then of course they are not going to use it, and you need to be respectful and not disruptive. So some of the things we're planning to look at is how we can create visualizations that are available and that are visible, but are not disruptive. You need to see a difference between virtual and real objects that you do not walk into one or the other. At the same time, you also do not want them to look artificial and attention-grabbing. If we have this future that you think of, there is lots and lots of potentials that we have to find the right ways to do it."

How should software toolkits be designed and how should the entire development be supported in an ecosystem of networked devices?

Multiple, networked devices are key to some of Elmqvist's works including some technology and toolkit support for multi-device environments and visualizations. Asked about an ecosystem of networked devices, he mentioned his Java-based research frameworks Hugin [54] and Munin [6]. "They all forced us to build things on a very low level. The good thing of course was that we could build them for different platforms and operating systems, because a visualization system of the future will consist of many different nodes, running on different types of devices."

"The work that came after was called PolyChrome [5], and more recently Vistrates [7]. In general, we recognized that the unifying layer that all the devices we are interested in seem to have is the web browser." Elmqvist further reasons about a distributed operating system, a display environment that is shared, that runs on many devices simultaneously. "We used to do in the past a lot of that work ourselves, which was very painful, but the ability to just build on web technologies has made life a lot easier. [...] The idea of using web technologies for this type of thing is the same insight that lies behind D3[3] and Vega[4], those visualization libraries that are just again based on web technologies. I think that is the right way to do it."

Are you still missing other ingredients needed to support ubiquitous visualization?

Elmqvist reflects about the challenge of computation on small mobile devices. "Even back when I was thinking about ubiquitous visualization, I had this notion that some of the nodes in the connected environmental devices could be a cloud device that

[3]Data-Driven Documents: https://d3js.org/
[4]Visualization Grammar Vega: https://vega.github.io/vega/

have significant computing power. So, essentially you could have a virtual machine in Amazon AWS, waiting for you to send to jobs, and on-demand you could get access to a lot of this computational power as needed, maybe for machine learning as you say or something else." Elmqvist continues: "We have a paper called VisHive [21], which is about: What if you don't have a computer or virtual machine in the cloud. Is there a way you can distribute the work using your local clouded devices? So if I have a smartwatch, tablet, smartphone or laptop, what if we could use those as a mini cluster." He talks about this peer-to-peer approach, where nothing has to be downloaded or installed and everything is just web-based.

Who are the people actually authoring such ubiquitous, distributed and highly adaptive visualizations?

It is already difficult to bring a commercial solution such as Tableau to mobile devices, but it will be much more difficult if they have to bring it to a completely distributed space, which also complicates authoring. Elmqvist agrees and offers one potential solution. "In Vistrates [7], we provide a data flow language, where you drag and drop components, and you connect the outputs of one to the inputs of another [. . .]." Even though drag-and-drop authoring is already simpler, it is still not trivial and requires an understanding of, for example, data flow. "But it is at least simpler than writing code. If you come across situations where you need a component in Vistrates that doesn't exist in the Vistrates library [. . .] you can implement an entirely new component from scratch. Or you can take an existing component and branch or fork it and modify it and save it back to the library."

For alternatives of authoring visualizations, Elmqvist then points to the recent work by Arvind Satyanarayan with Lyra [78], or Leo Zhicheng Liu's 'Data Illustrator'[5], or Bongshin Lee's and colleagues' Charticulator[6]. "All these are great examples of drag and drop visualization creation, even for really complex and advanced visualizations that you don't need to choose from a chart gallery."

These examples that Elmqvist provided can be summarized as *End-User Visualization* environments, very much like environments for End-User Software Engineering. In a way, to democratize authoring of visualizations and to make their production accessible to everyone could be a crucial ingredient for ubiquitous visualizations.

Could machine learning or AI help us to provide a solution for contextual adaptation?

Earlier in the interview we had talked about context adaptation for mobile visualizations. One way to achieve this technically is to encode these adaptations manually by programmers, another to achieve this by means of artificial intelligence (AI). Asked about the latter, Elmqvist responds: "With Vistribute [40], we used rules of thumb that we then validated based on a user study. But, how could it be done? It would be exciting if you could take the 'Show Me' feature that Tableau has, which is essentially

[5]Data Illustrator for creating infographics and data visualizations without programming: http://data-illustrator.com/

[6]Charticulator for creating chart designs without programming: https://charticulator.com/

Jock Mackinlay's PhD thesis from 1986, implemented 20 years later. There you can say, here is which data I am interested in, and the system is going to tell me how to visualize it most effectively. [. . .] If we could have a similar approach to not just the visualization themselves and the data, but also the devices that are available so that you can automatically make decisions to optimize depending on the task the person has. [. . .] I wonder if there are things we could do beyond rules of thumb, maybe, as you said, if we get a big enough training data set to create a machine learning model that can do this for us. We need to collect a lot of real world, in-the-wild data and use the data we collect to figure out what people's preferences are."

How do you expect people to interact with future visualizations? Will there be a mix of technologies, interaction techniques or maybe just speech – what is your opinion?

"As for speech, Arjun Srinivasan at Georgia Tech has done some interesting work there with Orko [84] and related topics. I think there is potential for using speech, but there are always difficulties in interacting using speech alone. So combinations are probably – especially for something as specific as data visualizations – more relevant, where you use touch and speech, or mouse and speech, or keyboard and speech and so on. Some of Arjun Srinivasan's work is interesting because it tries to define the affordances of each modality and how it can be used."

Elmqvist also advocates other modalities beside mouse, keyboard, and even touch. "Pens were out of fashion for a while, but now they have their comeback to some degree. They could be useful for more precise tasks. And I know, [. . .] you worked on how gaze can be used as an input modality; I think this could be interesting, also using facial expressions." He also considered proxemics in a paper with Sriram Karthik Badam [4]. "Basically, how you relate to other people, whether you look at them, you face them, how close you are to them or to physical objects, whether you hold your phone facing yourself or someone else. All these information could also be useful. If you can capture it, often that means you need an intelligent space, that has cameras to track people in the room."

"We've done some work on gestures and full body interaction, pointing and so on. [. . .] Providing tactile feedback could be another option. I think all these are potential ways and exciting opportunities. They all have their roles, their strengths and weaknesses, I think we need to figure them out and generate not just a visualization grammar or vocabulary, but also what input devices and output devices we have and how to best map them to the available data and what tasks people want to do."

People's sensory bandwidth is limited, and if they are overwhelmed by interactive visualizations everywhere, shouldn't there be some kind of mindful and respectful use?

People might be overwhelmed by the various options of how to interact with a visualization and no longer know whether to use proximity, gaze, gestures, or speech. Elmqvist argues "We already deal with this in data visualization, because we recognize that people can only see so many visual items at the same time. So there has been a lot of work to minimize clutter and find visual summaries that are not overwhelming. But, it is absolutely true, that the potential for overwhelming the users is even more if you include other sensory modalities, like sound, and everywhere you look there is going to be a bar chart, and everything is going moving and jumping. We have to be respectful of the individuals, find out the best way to do things. Sometimes that may even go so far as to think of the human as the limiting resource we have to manage. And this sounds a little dystopian of course. Just like we think of a computer's memory or rendering performance as a resource we have to manage, we could think about the human's limited resources we have to respect. [...] We might want to manage interruptions and the person's attention. I think it is more about being respectful to human's capacities rather than scheduling, which sounds like we treat the person as a computer. I think, it is more that we respect boundaries."

In your Ubilytics work, you assume that people will actually perform analytics tasks in the wild, but won't they rather deal mostly with easier, glanceable visualizations?

"That's my feeling too, I may be wrong. I have a sense that most people prefer the controlled confines of a space like their office or home for accomplishing more involved tasks, because just how human beings work with the amount of interactions you might have in a mobile setting and things like safety and so on. So yes, I would think that there will be mostly use cases that have to do with opportunistic or serendipitous in-situ decision-making, maybe not so many long-term decisions. Like I said in the beginning, we were trying to find those apps that take good advantage of the fact that people are in a physical space, where the space makes the difference."

Do you envision more interaction happening between people, more collaboration if they use ubiquitous visualizations in the future?

"Most devices are designed for focused use of single users. Smartphones will remain personal devices, because they're so tied up to individuals. 10-15 years ago, new devices came about which were larger, like wall-sized displays or tabletop displays. Because of their orientation and size, they were more inviting for collaborative use. And tabletops and large displays, I am not going to say that they are obsolete, but we see less of them now, because we've moved more to a mobile setting. The question you might want to ask, what is equivalent of a collaborative display or device in an entirely mobile setting. I don't know."

He argued in the following that mobile projections (cf. [22]), even though obviously intended for sharing content or visualizations, are not the right way to do it either. "If it's AR, that is our future, maybe that means that there will be ways where you can signify this is something that not just you see, but also other people see. That allows you to collaborate better. But if you go towards a more physical display future, it's hard to predict. We have one project in our lab where we are looking at displays on devices and projectors on some drones. And some of my colleagues at Maryland had a drone that follows the user, a little like a floating display that follows you around. Very physical, kind of scary. [...] But it could potentially be useful for multiple users."

Niklas Elmqvist concluded the interview with a comment that he was inspired by our discussion and that many things are left to be done in this exciting space.

9.5 SEAN WHITE ON SITUATED AUGMENTED REALITY

At the time of writing, Sean White was the Chief Research & Development Officer for Mozilla. At Mozilla, Sean has championed the development of Mozilla Mixed Reality, including the Firefox Reality browser for VR. He has published pioneering research in the area of augmented reality and visualization, in particular contributing of the notion of *situated visualization* [93].

Situated visualizations, often presented in augmented reality, display data directly within the context where the data is relevant, such as overlaying graphs or visualizations of harmful gas emissions directly over a view of a streetscape. By viewing emissions data in situ, urban designers reported being better able to understand factors causing air quality problems than when viewing a data-annotated map. Interesting findings from the *SiteLens* project included that more literal visualizations such as animated smoke clouds were more effective and relatable in situ over more traditional chart types overlaid on the environment. The disconnect of using stale data in situ was raised as an opportunity which in the ten years since the work is more readily possible with the growth of connected devices, cloud data architectures, and IoT sensors in the environment.

White has been engaged with the community including teaching "HCI Issues in Mixed & Augmented Reality" at Stanford, mentoring for Engineers without Borders, and serving on the Steering Committee for IEEE's International Symposium on Mixed and Augmented Reality (ISMAR). We met with him to garner his reflections on ubiquitous visualization, from his industrial research and development perspective.

What does mobile visualization mean to you? How do you see it being used today?

White started by stating his view that visualization is not just communication, but also important to help people think through data, to extend perception/cognition. He said, "Mobile then is the context. It's the ways in which our computational systems extend our abilities to analyze in the context in which it's needed [. . .] there's a secondary aspect where it's just reachable; that is, I happen to be able to access it while I'm there." White continued to explain that in industry, some initiatives are taking place which build on his early research, such as AR/VR enabled web browsers that can bring visualization into the world around you. For example, embedding temperature sensors in AR headsets to overlay that information in the world around the user.

How do you envision mobile visualization contextually adapting to aid a user's activity?

White believes that by putting the visualization in context the learning and cognition are increased: "There's some reasonable amount of evidence around that. I think it makes more sense when it is situated and you are closer to the sources of data whether that is sensors or other aspects of the world that you're trying to visualize." Mobile visualization generally gives a first-person point of view; the viewer is embedded in the visualization directly. However, "some of the work of Kalkofen [48] gives a sort of third person point of view within a first person point of view."

What different application areas and target user groups do you envision in the future for the consumption of data on mobile devices (versus visualizations on the desktop)?

White envisions immediate applications in industrial and medical environments. In medical applications, he suspects augmented visualizations, where content is projected on the users body, showing veins on the arms could become routine in guiding a nurse when performing blood extractions, for example. Additional means for quickly allowing one to glance at biometric data, such as blood glucose levels at periodic intervals during the day, could be available to patients and also their doctors, the moment the individual steps into the doctor's office. In industrial settings, White envisions visualizations becoming commonplace with advances in LIDAR (LIght Detection And Ranging) technologies. These would enable indoor way finding, a key element for tracking objects in manufacturing plants.

While the above two applications seem to be immediate opportunities, White further envisioned that mobile visualizations would be directed at the masses. At the time of this writing, the COVID-19 pandemic was taking its roots worldwide. White suggested that novel sensors could enable timely COVID-19 tracing. The ability to present information, that is at the same time aesthetically pleasing yet informative could be designed and tailored to the masses to make rapid decisions.

What do you see as key use cases for mobile/ubiquitous visualizations?

White believes an immediate use case is in medicine due to the utilitarian nature of the field, due to it involving in-the-moment decisions, and it being necessary and important. Given that surgeons are already willing to wear glasses as part of their responsibilities, for example for surgery, it may seem like an immediate opportunity for mobile visualization. Similarly, White believes maintenance and repair to be the mechanical version of the needs in the medical fields. In this use case, a mixed reality (MR) web browser could intelligently mash up web content, organize it cohesively, and make it available for remote guidance and remote repair.

What is the current big thing for mobile visualization? And what do you think will be next?

White said, "I would love to see visualization used to ask more questions" and compared it to how mobile visualizations can spark the same degree of curiosity as a piece of good art. Another growing interest is in allowing more views of the data to enable social cohesiveness and collaborative interactions around the visualization. White wishes to see these forms of collaborative spaces to enable creative, social and analytical in-place activities, "to be able to have multiple people visualizing in the space together." White also expects that mobile visualizations will see an evolution as a number of developments converge, particularly with head-worn displays. He expects information to flow more fluidly across multiple modalities including voice, audio and space. Development such as the iPad's LIDAR sensing can lead to interesting ways to incorporate the background and mesh it into the foreground as a whole.

What about scenarios where data can be mobile and with the user? The devices and displays would then be proactive, and adapt to the user, rather than presenting generic information that is the same for everyone?

White alludes to less is more in such scenarios, and to the importance of allowing people to still have the feeling of maintaining control. The idea of subtlety with minimal pre-attentive cues and lightweight hints could be a rich field to explore. He recalls his experience with the first Mac systems where users could just slap hundreds of fonts on a flyer, and thus they did. Over time people took into account perception, aesthetics, and the world generally got better at design. White believes the same is true with current mobile visualizations: navigating those is much like being in a fighter cockpit. Instead, subtle cues, such as those from a friend to indicate in which direction to go while walking down an unknown road together, could enhance one's sense of control while relying on the system and its knowledge of the world and the user's context.

How do you see mobile visualization transitioning to ubiquitous visualization? What does ubiquitous visualization mean to you?

"The pithy answer is: your glasses." White tends to think of it as the distinction of *present-in-hand* versus *ready-to-hand*. "In the best scenario ubiquitous visualization will be present and ready to use as an extension, rather than mobile, which is something I have to pull out of my pocket. We still have a ways to go to get there." White said, "It's a really different usage: when you first start talking to people about mobile visualization, they have a model of always on, always present, always there. Then you get to the realities of it and you have a thing that you can pull out or put on for a moment." White reflected on his work with botanists, who received real benefit from situated mobile visualization using large AR glasses. They were willing to do it because "they cared, because it had a real utility." He said, "All the things we encounter in the world when we are there, are situated. What I am looking for is that mix, where ubiquitous visualization means that I have the option to always be situated in my learning, the things that I create, my interactions with other people." That takes a combination of a lot of new hardware, software breakthroughs, infrastructure, and all the visualizations we would need to create for this platform, but, it would lead to a better way to interact. White stated one of his long-term personal goals "to have us lift up our heads, no longer looking down at our phones. Transitioning to ubiquitous visualization would be part of that. It means we are more human." In contrast to a monocle or other device that has to be pulled out, glasses are already present, breaking down the barrier of interaction inertia.

Has the design and development of mobile visualizations become a key priority in industry?

White confirmed there is recognition in industry that visualization and visual communication are important, along with design, HCI, and user needs. “Visualization in general, but you could consider it mobile visualization, can be powerful for communication, but also for understanding. The industry itself, let’s say the mobile phone, device, web-application industries, realize that to make good decisions, you need good visualizations. To make good decisions in the moment, you need mobile visualizations.” White reflected on the impact of the mobile revolution – there are fewer people now using desktops than mobile devices; we have now a whole generation who are mobile first. This, White said, is one of the reasons the phone industry is investing significantly in both software and sensors. Phones started as a mini version of a desktop, a metaphorical “horseless carriage” but are slowly transforming “into something more unique, like the Star Trek tri-corder.” Situated visualization doesn’t have to be constrained to spatially situated, it could be situated through understanding the world, the people around me, the air quality, the impacts of my movements.

In your work, you have also paid attention to how one can best interact with situated visualization in AR (e.g. gestural hints for tangible AR [96], shake menu techniques [95]). What do you think is key in terms of supporting effective interaction when we move to more ubiquitous visualization?

White separated the discussion into the deployment platforms: there is still a broad design space for phones and watches — a lot of experimentation is possible beyond the things we are familiar with. “On the web we build toolkits in an open source way and then suddenly, everbody’s using it and building on it. This has not really existed for other kinds of displays. The two I’m thinking of in particular are AR/VR displays and auditory displays.” White lamented that for AR/VR displays, the tools built 5 or 10 years ago can’t now be used by researchers, students, and industry because the systems are gone. “One of the reasons I like toolkits is for the longevity — there is a platform aspect.” Outside of visualization, White thinks the same is true for audio, that there will be a renaissance around the interactions for audio with the new earbud technology. “After that will be the progression from the 100 fonts to a couple.”, meaning the design will coalesce around key interactions that work well. White advocates for a multi-disciplinary team approach consisting of research scientists, designers, cognitive psychologists. “Artists too. They are always adding in the extra part that other people are not thinking about.”

9.6 YVONNE ROGERS ON VISUALIZATIONS FOR SOCIAL EMPOWERMENT

Yvonne Rogers[7] is the director of the Interaction Centre at University College London (UCLIC), a professor of Interaction Design and the deputy head of department in the Computer Science Department. Former positions include professorships at the Open University, Indiana University and Sussex University; she has also been a visiting professor at University Cape Town, University of Melbourne, Queensland University of Technology, Stanford University, Apple and UCSD. She is internationally renowned for her work in human-computer interaction, interaction design and ubiquitous computing. She was awarded a prestigious EPSRC dream fellowship to rethink the relationship between ageing, computing and creativity. She is passionate about designing computers that are engaging, exciting and even provocative. She has published over 250 articles, and is a co-author of the definitive textbook on Interaction Design that has sold over 200,000 copies worldwide and been translated into 6 languages.

Several of Yvonne's research projects are of relevance to this book chapter. Yvonne's early work on Ambient Wood [76] within the Equator project explored the use of mobile data collection and visualization as part of an educational experience for children to learn about biology. More recently, Yvonne and her team investigated how to engage communities with data and the Internet of Things in urban settings within the "Intel Collaborative Research Institute (ICRI) on Sustainable Connected Cities". Examples of such projects include Tidy Street [11], PhysiKit, and physical installations to engage citizens with data such as VoxBox [30] and Sens-US [29].

What does mobile visualization mean to you?

Yvonne mentions that mobile visualizations are those that "you might use in person in-situ whilst you are doing another activity as opposed to those that appear on a desktop or a tabletop or a wall that might be shared or used by an individual sitting down or standing."

What do you see as the main use cases of mobile visualization?

Her first experience with mobile visualization was in the field of education in the context of the Ambient Wood project [76]. In that project, students had access to visualizations of data that they were collecting in-situ. Having this at hand "enabled them to couple the data that they were collecting with the learning activity that they were involved in." She also mentions that "We have much more affordable, adaptable, flexible sensing technology than in the old days. You can collect data and visualize it in the moment (both the actual data and the other samples that have been collected).

[7] Note that we refer to our interviewee Yvonne Rogers by "Yvonne", as she preferred her first name over "Rogers".

I think in an educational context, particularly for field work, it is a very powerful tool to use."

She thinks that digital healthcare is going to be a use case for mobile visualization where the combination of electronic records and sensing technology will allow healthcare workers and researchers to make decisions in real time. Additionally, fields such as personal informatics, sports, and exercise will benefit, "where people like to see data in the moment and how well they've done compared to other times and periods." Similar to Willett, she also thinks that looking at data in context in the field of retail could be another application area.

What do you see as the benefits of the visualization being mobile?

She mentions that they had an "aha!" moment in the Ambient Wood project [76] where "a simple visualization was shown in the moment. Moisture and light level infographics were used to convey relative levels that were seen by students/users, which they used in their learning activities." Seeing in the moment enabled the students to generate hypotheses on the fly (whether something would be lighter/darker) and take initiative in their own learning. It was much more powerful and fulfilling than just completing tasks.

Recently, Yvonne's PhD student Susan Lechelt has been working with students to think about data collection and what it means in terms of their own data. She had students measure their heart rate, electrocardiogram, and galvanic sweat response (to measure emotional response), and then asked them to answer questions such as 'do you fancy X (where X was someone in their class)?'. This provided them with readings they could use to determine if the person was telling the truth when answering the questions. Yvonne mentioned that "it got them to think about the reliability and accuracy of the data and not taking it for granted. What does the data they collect represent?" It allows students to collect and sense things about the body and then start questioning what that data means. Learning in those contexts is one of the most powerful uses of data and visualization.

How do you envision mobile visualization contextually adapting to aid a user's activity?

In terms of the visualization contextually providing users cues and hints, Yvonne mentions that walking/cycling apps do a great job of notifying the user when they reach a goal and they also some times encourage the user to keep going. She said that a visualization may "motivate you more" and make you want to keep going.

She referenced the Balance Table [77] project where the authors used a series of LEDs on a tabletop to convey who was talking more or less in a conversation. She mentioned that the "people who didn't speak much didn't like that they were not talking a lot and people who spoke more did not look at the visualization." This kind of ambient display could be used in mobile contexts, such as during remote meetings, showing who is talking or contributing the most. Somewhat controversially, it might be a great way of letting people know - in the form of a peripheral awareness norm – that they should pipe down or speak up.

Yvonne said that we need to be careful with contextually aware approaches to mobile visualization as there are many important considerations such as whether it is the right time to display the right data or the reason why we are providing contextual information to begin with. How would an adaptive interface detect crucial aspects of the person or the environment they are in to make the right decision with respect to showing contextual information? This would be different than previous work on adaptive interfaces that changed based on the completion of a task or adapted to a user's style of interaction.

What do you think is the current big thing and what do you think would be next for mobile visualization?

Yvonne referenced the interactive visualizations that are being developed to visualize the spread of COVID-19 in different countries. She said that it was teaching people to "read graphs and visualizations in a different way." She wondered if new ways of communicating data can be learned and whether individuals were reading those graphs correctly as some of the graphs seen in print and media are fairly complex. It is a great opportunity to think of how to design mobile visualisations that are more accessible to the general public.

She also mentioned that "the current widespread use of visualizations may increase awareness of visualization techniques that they can use in other contexts (e.g. weather, climate change, carbon emission footprint, etc.)" She would like to see more examples of accessible visualizations being developed and used to show that the world is getting worse or better (air quality, emissions, deforestation, and so on).

What does ubiquitous visualization mean to you? How do you see mobile visualization transitioning to "ubiquitous visualization"?

Yvonne mentioned that ubiquitous visualization could "include visualizations that appear in the physical environment, such as Picadilly Circus, or on an individual's smartwatch, a public display in a shopping mall, or even in nature, such as a forest. Ubiquitous means anywhere – personal, social, or environment. Some of the early ambient displays might be considered ubiquitous visualizations, for example some of the early art projects that showed the amount of CO2 emissions by having dynamic visualizations appear on a wall. These were meant to make a statement and provoke the public into action." Many of them did.

What do you see as the most exciting aspects of bringing data and particularly data visualization into people's everyday lives?

Yvonne described her role in the "Intel Collaborative Research Institute (ICRI) on Connected Sustainable Cities", where her team researched how to engage communities in the urban environment and collect data about the environment. She said that the types of visualizations that they developed "were coupled very visibly with the way the data was collected."

She referenced her work on the Tidy Street project [11] and the research of her former PhD student (Lisa Koeman) on *Visualising Mill Road* [58]. She asked people on the street to vote on questions asked each day about topics concerning them (e.g., how safe do you feel?) and then displayed the results in the form of an infographic that was chalked on a street pavement (e.g., the perceived level of safety). Yvonne mentions: "In the Tidy Street project, the goal was to collect the householder's electricity consumption for each day, feed it into an app, and then display the average usage for the street as a public visualization, to get people to act on it to maybe reduce their energy consumption."

She likes to "think about how communities come together and ask questions that they may have not asked and what it means in terms of urban living." She likes to focus on social engagement and empowerment rather than more utilitarian civic engagement related to an individual's neighborhood (e.g., potholes filled, new lampposts, etc.). She mentioned how these projects "were more engaging in terms of showing the residents who they were and what they cared about and how safe the streets were and what were the things that troubled them."

She then discussed the PhysiKit [42] project that facilitated the collection of data in people's homes using the Open Source Smart Citizen kit. PhysiKit contained temperature, light, noise, and humidity sensors that could be programmed to notify the user based on user-defined rules. The goal was to get people to think about the consequences of their actions such as the humidity sensor would alert the user to turn on the exhaust fan if the humidity in a room was too high, or if the ambient noise in a room was too high the user would be notified about it. In one particularly interesting example, they played a potted plant on a motor that would rotate the plant based on the light exposure the sensor under it had received that day.

The collected data from the open source Smart Citizen Kit "was presented as a dashboard on a website, so people didn't look at it." The goal with PhysiKit was to get people to think about the consequences of their actions on different sensor readings. They were also given a tangible device they could program to alert them to change in their environment (e.g. when the CO2 level was high) so they could understand the data in a more meaningful way. She summarized by saying that "Sensing, representing, and acting upon it" are the three coupled things that are common to all of her projects.

Would you like to share any surprising, empowering, or inspiring examples from your team's projects (for example, Tidy Street [11], PhysiKit [42], Roam.io [41] , the lambent shopping handle [49], PlayBats [50], ...)?

Yvonne mentioned the Roam.io [41] project that focused on tracking people on the island of Madeira through their mobile phones and hotspots to help understand the impact of large-scale tourism on the small island. Passersby were very helpful in providing more information beyond what the automated tracking technology offered. This gave the researchers a much better picture of where the tourists went, which parts of the island were visited the most and so on – without identifying any individual people. She also mentioned how her recent research has shown how people are more concerned about data privacy now than they have been in the past. That made her reflect more on the issues related to data collection, storage, usage, and increasing awareness of the users whose data is being collected.

She said that while "General Data Protection Regulation (GDPR) helps in these research projects, privacy has become an increasingly more important concern. While we can and do anonymise our data, we can always collect a lot more. A key question we need to consider more, is what is the minimum amount of data we can collect in order to answer our research question?"

She referenced the project of her current student (Lucy Walsh) that explored how to increase people's awareness of the data being collected about their usage when on a webpage. Part of the project involved developing a tangible device intended to sit on a user's desk that could light up to let them know what data was being collected about them. She said that the next generation of researchers "can think of new ways to alert people about what they are worried about such as the kinds of data being collected."

In a lot of your work (e.g. PhysiKit [42], Voxbox [30], Sens-Us [29], physicality and tangibility play a big role. Do you see this as something that is a nice add-on to have for more engagement, or is that really a key thing to consider?

Yvonne remembers how some of her earlier research started with exploring how to embed the Internet of Things (IoT) technology in a public building to increase awareness of its use. Presenting this back to the inhabitants and visitors of the building as a dynamic visualization can draw their attention to topics, behaviors or other aspects that they would normally overlook. She believes that "something physical is very effective, as it can draw people's attention in ways that a mobile app cannot." She said that her students and she love to build things and incorporating tangibility provides a richer palette (rather than staying only digital).

She predicts that in "in 10 years or so, we may even see plant-based interfaces." She mentioned that there is "plant-based clothing that can change and glow." She said that the next generation of interfaces will be innovative forms of fusing the physical, the digital and the tangible.

With the proliferation of Makerspaces and 3D printers, designing and creating interfaces that are attractive, aesthetic, *and* functional has become more accessible and affordable. Different ways to increase civic engagement and awareness may emerge from such interfaces and some of these may be citizen-driven in line with the increased enthusiasm behind the citizen science movement.

How should we take into account mindful technology for ubiquitous data visualization avoiding things like data addiction?

Yvonne explained that she was on a train recently that stopped at Gatwick airport. There she saw about 20 kids in groups of 4–5 that all had their heads down, looking at their phones. She lamented that "Everyone is looking down at their phones. It would be great if we can design ways to get them to *look up and look out*." One way of doing this, is to create new forms of public mobile visualizations that could shift people's attention from their phones to the environment around them. She said: "For example, in a coffee shop, if we could see how many cups of coffee had been bought that day compared to say, tea, it might get them thinking why is that happening? While seemingly trivial, it can feed into our fascination with factoids. The visualisations might show how much water has been used or saved that day, how many people had brought their one cup, how much the cafe had recycled, how much they had donated to a charity based on the number of lattes sold, and so on. Other topics could also be explored that people might be interested in but which can't currently be seen or conveyed." She urged researchers to think of creative ways to "help people have conversations that don't require always being mediated by your phone."

She mentioned the inspiration for the lambent shopping handle project [49], where a simple LED visualization was integrated with a shopping cart to show certain information about products they were interested in buying such as the number of food miles, whether organic, whether it contained nuts. This enabled shoppers to rapidly see at a glance when comparing different brands for products. She talked about how the prototype they built was featured on the "Gadget Man"[8] show with Richard Ayoade, who "really liked it for the fact that it was integrated into the shopping cart." She added that "When we show the shopping handle to other people, they frequently ask why don't you make it into a mobile app?." She said that "They are missing the whole point about how it's actually embedded into the device itself. It may be too expensive to put it in the handle [now], but it may not be in the future."

How do you see the intersection between (contextual) data collection and the potential for in-situ data visualization?

Yvonne said that "the coupling between data collection and visualization makes it meaningful. If you only provide dashboards that are visualizing what happens in London in terms of air quality, whether the underground is running, etc, people might glance at it once or twice, then forget about it. But if you engage them in the data collection, it becomes much more interesting and meaningful then."

She referenced the Tidy Street [11] project again and said that "if you were engaged personally in reducing energy consumption, then you become much more engaged and motivated to continue." She said that connecting the two (data collection and visualization) makes it more meaningful to the participants.

What do you think about future form factors for visualizations?

Yvonne mentioned that visualizations on a phone or smartwatch will continue for personal use and "they seem to be quite powerful for some people." She would also like to see visualizations that "can be in the environment for people to share and reflect on for groups of people to look at and possibly engage with." In the future, other materials may be used, such as clothing, toys, floors, ceilings and even holograms.

[8] https://www.channel4.com/programmes/gadget-man/

Will authoring data visualizations become more "democratic", as you explored in PhysiKit, and will it — like taking photos and video editing — become accessible to everyone? What are the remaining challenges?

Yvonne mentioned 3D printed work by Kim Sauvé [80] where she printed 3D shapes of someone's activity data and then asked them to reflect on it. She also mentioned Khot et al.'s EdiPulse project [53] work on printing 3D shapes from chocolate. She mentioned how "3D printing your own data makes something that is intangible a talking point again."

She also thinks that new 3D authoring tools could be used by people who have difficulty communicating with others. For example, people on the autism spectrum could print their data to "express something that they don't normally express or they find it hard to talk about and maybe through the use of this 3D artefact, they can talk through it and that this could help them communicate better."

There will always be challenges for making our data democratic – not least reassuring people that it is being used for their benefit or society. However, new kinds of visualisations can increase the transparency of how the data is collected and whether it contravenes their privacy rights.

Yvonne's oeuvre has a consistent thread of giving a voice to the people. Her research philosophy goes much beyond just functional things (what can we do for you). Her research group has worked on projects that use technology to raise awareness on important issues and to give citizens a voice, particularly for urban living where people may feel more isolated.

From a methodological perspective, is it time for the visualization community to embrace HCI's "turn to the wild?"

When we asked Yvonne about the relevance of her work on HCI research "in the wild" [75, 72, 20] to the move towards mobile and ubiquitous visualization, where we increasingly see visualizations introduced into a wide variety of different settings and situations, she replied:

"You know what my answer is going to be. Absolutely! It is about time. I think if you really want to understand how people use visualizations, it is important to move out of the lab. I think there is still some important research to be done in the lab in terms of legibility and response time for different kinds of visualizations. But, if you want to see actually how people will use them and reflect upon them in their everyday lives, then you need to go into the world."

9.7 DISCUSSION AND OVERALL REFLECTION

In this section, we reflect on common themes across the four interviews, and discuss what we can learn from them regarding the future of mobile visualization.

9.7.1 Mobile versus Ubiquitous Visualization

We asked all of our interviewees what the the terms "mobile visualization" and "ubiquitous visualization" meant to them. While each interviewee had a different perspective on this, there were some commonalities in their answers. Willett noted that, for him, mobile visualization is mostly about the form factor, about the visualization being shown on a mobile platform such as a phone or tablet. He also noted that even though the data is made available in a mobile setting, this does not always mean that the visualization is more situated with the tasks that it is supposed to support. Elmqvist sees mobile visualization as anything that is not using a personal computer and that focuses on situations where people are on the go. He mentioned that what sets its apart is the on-the-go aspect and supporting decision-making in-situ, which would be harder and require more time to do offline on a desktop device in an office. To Rogers, mobile visualizations are personal visualizations that you might use while doing another activity. While some of our interviewees see mobile visualization as being tied to current (touchscreen-based) mobile hardware platforms, White provided other examples of mobile visualization in AR and MR. White said two aspects of a mobile visualization were important to him: context—the ways in which the mobile visualization can extend our abilities in terms of cognition and learning to analyze data in the situation in which it is needed; and reachability—the fact that one can access it while in that context.

When confronted with the term "ubiquitous visualization", our interviewees had different ways of distinguishing this from mobile visualization. Willett mentioned that the end goal of ubiquitous visualization is to have access to data where and when it is useful. Out of several visions for ubiquitous visualization, he finds the ones that are technology-agnostic more satisfying as they could be realized with technology platforms that are currently available and also with future technology that is still infeasible for the next couple of decades. Good examples of ubiquitous visualization according to Willett are LEDs in parking garages indicating availability of parking spaces and the integrated LEDs in bicycle lanes. To Elqmvist, the key difference is that ubiquitous visualization would be far more integrated into real-world contexts, with possible use of AR or other augmentation technologies. However, like Willett, Elmqvist also mentions that we should consider how we could already achieve ubiquitous visualization with current technologies. Elmqvist mentioned Pokémon Go as a notable example that successfully integrated the real and the virtual world. Rogers notes that ubiquitous visualizations would appear anywhere, in personal settings and social settings, and everywhere in our environment. She notes that some of the early ambient displays could be considered ubiquitous visualizations. A key part of this, according to Rogers, is that these visualizations are meant to make a statement, to provoke the public, or to share with the public. On the other hand, White differentiated between mobile and ubiquitous visualization in terms of the visualization being (in Heidegger's terms) either "present-in-hand" or "ready-at-hand". He gave the example of pulling a phone out of one's pocket versus having access to AR visualizations integrated in one's glasses. While both support visualizations that are "always there", it takes more effort to pull out your phone compared to just turning on the visualization with your AR glasses. White explained that the goal of ubiquitous visualization to him is to have the option to be always situated in one's learning.

These comments suggest that the key aspect of mobile visualization is the ability to access and use the visualization in-situ. Ubiquitous visualization seems to push this idea even further to make the visualization more easily accessible, available, and in particular as noted by our interviewees, more situated within people's activities and settings. Additionally, our interviewees suggested that ubiquitous visualization should also go beyond the personal aspects of current mobile devices and allows for more shared and collaborative use. A common theme in the interviews was that there are few examples of mobile visualizations that really take advantage of being available in a mobile context. Indeed, many mobile visualizations are ports of existing visualizations designed for a smaller form factor, and only take contextual aspects (such as location) into account in a limited way. While location is of course only one of the aspects of context that can be taken into account (other aspects include the social setting, who one is with, and the activities one is engaged in), Elmqvist emphasized the potential of using place as an index into the virtual world of data. Some of the notable contextually-relevant examples that were mentioned by our interviewees include mobile visualizations in car dashboards (Willett), in-situ collection and visualization in an educational context as in Ambient Wood [76] (Rogers), and a mobile AR electronic field guide for botanists [94, 98] (White). This suggests that as part of a move towards ubiquitous visualization, we may initially see more strongly situated mobile visualizations that take advantage of current hardware platforms.

9.7.2 Challenge: Information Overload

Potential information overload is already a challenge with visualization on mobile devices, due to the limited form factor (see Chapter 3). Our interviewees mentioned that this challenge would only be exacerbated as we move more towards ubiquitous visualization. Willett differentiated between information density and information complexity of a visualization and mentioned that the problem mostly lies with information complexity. He mentioned some possible ways to deal with this such as visual summaries, glanceable visualizations, and a staged approach to revealing data. Similarly, Elmqvist brought up the challenge of making visualizations, data, and displays available everywhere without polluting people's virtual space. He argued that designers need to be respectful of the user. White likened current mobile visualizations with being in a fighter jet cockpit. Over time, he expects we will develop a better sense of design and aesthetics, and subtlety in the design of mobile visualizations. Regarding information overload, Rogers mentioned her Physikit project [42], where data becomes visible at certain moments in time to remind people that a certain event occurred, for example, when a certain level of air quality or CO_2 concentration has been reached. In line with Willett's suggestion of a staged approach, a promising way to avoid information overload could be to facilitate opt-in and opt-out choices, as explored in proxemic interaction and interaction with public displays [12, 71], where one would have to explicitly opt-in to or have an option to opt-out of being presented with data visualizations. This also reminded us of prior discussions in the ubiquitous computing and HCI communities with respect to interaction in the periphery [8, 16, 47] and Weiser's notion of calm technology [91]. However, as our interviewee Yvonne Rogers has argued previously, we may also want to design for engaging and playful (rather than calm) experiences [74]. As mentioned above, Rogers argued that she believes a key aspect for ubiquitous visualizations is to provoke and engage people.

Being exposed to ever-increasing data and data visualizations may also have negative consequences. When data is disturbing, being exposed to visualizations of that data may make people anxious. As seen during the COVID-19 pandemic, people reported feeling anxious about news reports and often refrained from following updates about the number of cases or deaths as a result of COVID-19. Chapter 7 on ethics and privacy challenges also discussed "data anxiety" that people may experience in terms of tracking personal health or activity data. This points to a related design challenge for ubiquitous visualization. Depending on the topic, making visualizations available everywhere and at any time may not only overwhelm people in terms of information overload, but may also have negative effects on people's mental health.

9.7.3 Challenge: People Looking Down at Their Mobile Devices

Several of our interviewees also mentioned how it is a common sight to see people just look down at their mobile devices and ignore their surroundings. Our interviewee Yvonne Rogers has previously questioned whether this is what we want from technology [73]. She distinguished between *mindless* interactions in which we are focused on ourselves and look down at our phone and *mindful* interactions in which we are mindful of others and the environment around us. In many ways, this is opposite to what our interviewees envision with ubiquitous visualization. Instead, ubiquitous visualization would aim at bringing us closer to each other and to provide us with more information about the environment in which we are currently residing, making us feel more in touch with it. A few comments from the interviews confirm this. Rogers notes that showing data in-situ could provide talking points to get people to interact socially. White specifically mentioned that one of his personal goals was to break the pattern of people looking down at their phones and he mentioned that transitioning to ubiquitous visualization could be an opportunity to address this challenge and be more human. White mentioned he wants visualizations to ask more questions and spark curiosity, similar to works of art. Rogers also brought up the idea of physical visualizations of data that are human-sized three-dimensional shapes so that people can explore data by walking around it, "more of a museum piece". Similar to Rogers, White also expressed a desire for visualizations that go beyond the personal and enable social cohesiveness and collaborative interactions around the visualization.

Reflecting on these discussion points, there is clearly much potential for ubiquitous visualization break this pattern that we see in current mobile devices by exploring more social, creative, provoking, and engaging aspects of data visualization, rather than focusing on analytic aspects alone.

9.7.4 Opportunity: Mobile Displays as a Way to Envision the Future

While several of our interviewees discuss visions of ubiquitous visualization using advanced technologies such as integrated retina displays or AR glasses, they also argue that we can already realize much of this vision with existing technologies. Moreover, Willett and Elmqvist both cast doubts on whether AR will be the single most optimal technology solution to achieve ubiquitous visualization. Willett notes that while AR and MR are receiving a lot of attention, many challenges still remain. An important challenge of AR/MR that Willett mentions is the difficulty of providing shared experiences using these technologies. Similarly, Elmqvist notes that AR is promising, but that “AR glasses will not be worn by everyone”, and that there are still large gaps that need to be addressed to reach that stage.

Instead, Willett and Elmqvist both point to *displays* as a promising technology platform that can be used in the short-term to realize ubiquitous visualization. Willett mentions that embedding increasingly cheaper displays and projections into everyday spaces could be a shortcut to this envisioned future that may still be 20 to 30 years away. Similarly, Elqmvist talks about his vision of “ubiquitous visual computing”, which is a version of ubiquitous computing [90] in which devices do not completely disappear nor are display-less or magic. As with making mobile visualizations more integrated with people’s everyday tasks, the use of many (small) situated displays [51] may be one of the first ways in which we see practical realizations of ubiquitous visualization. In particular, small, low-cost, and power-efficient e-ink displays have shown promise for exploring and prototyping the use of visualizations in everyday spaces [2, 14]. If the costs of displays continue to decrease, a key difference would be that such displays may not be used as personal devices anymore (as we currently see with current mobile devices). Instead, they could be repurposed and reused many times, depending on the scenario. This is more in line with Weiser’s original vision of the “tab” [90] (roughly the form factor of today’s smartphone) as a shared and “throw-away” device that one would pick up when needed.

Finally, we want to stress that there are also rich opportunities for ubiquitous visualization that go beyond displays, such as presenting data through physicalization [45], physical actuation as in Jeremijenko’s Live Wire [92] or sonification, which we will come back to in Section 9.7.6.

9.7.5 The Web as a Technology Platform

The web is already an essential platform for mobile visualization, with toolkits such as D3 [13] or Vega-Lite [79] that integrate with existing web technologies to enable access to data visualizations on a wide variety of devices. According to some of our interviewees, we can build upon the existing strength of the web as a common platform for mobile visualization when looking at a possible platform to facilitate development of ubiquitous visualizations. Both Elmqvist and White specifically mention the use of web technologies as a generic and widely-available platform that could enable ubiquitous visualization. According to Elqmvist, the key advantage of the web as a platform is that it does not require any specialized software, everything is running in JavaScript in the browser. All one needs is a capable web browser, which more and more devices are nowadays capable of running. Elmqvist noted that the use of web browsers could bring us closer to a distributed operating system, a shared display environment that runs on many devices simultaneously, while noting that this may also mean that some devices may have to offload computation to more powerful nodes due to limited computational capabilities. Similarly, Sean White discussed the opportunities of a mixed-reality web browser (e.g. Firefox Reality [63]) which could intelligently mash up web content for use in particular settings. White contrasted the use of open source toolkits on the web that everyone can use and build upon with the tools for AR/VR that were built 5–10 years ago that cannot be used by researchers, students or industry anymore since the systems do not exist anymore. In summary, this points to much potential for the use of the web as a shared platform to develop future ubiquitous visualization systems, building on the success of prior web visualization toolkits.

9.7.6 How Will We Interact with Ubiquitous Visualization?

As discussed in Chapter 3, visualizations on mobile devices can support a number of different interaction modalities, such as touch, voice and spatial interaction (sometimes even across multiple mobile and stationary devices). A key challenge, however, has been with discoverability and consistency of these interactions: narrowing these possibilities down to common interaction patterns that work well for the activities and tasks at hand. Visualizations also often need to be completely reimagined for mobile use due to differences in display size and resolution, precision in interaction, and the constraints of use on the go (see Chapter 2). To understand what this will mean for interaction with ubiquitous visualization, we asked our interviewees how they envisioned interacting with ubiquitous visualizations. As discussed above, White mentioned the use of AR glasses and having the visualization always at hand, whenever we needed to access it. Proxemics [32] was mentioned by Willett as a possible solution to stage or scaffold the amount of information that was shown to the user and address the risk of potentially overwhelming users. Elmqvist particularly mentioned the use of different input modalities, including speech, body interaction, proxemics, and tactile feedback, and mentions a need to map out what is possible and what is most appropriate for different tasks and purposes. White mentioned the coming renaissance in audio interaction, which will open up audio soundscape design possibilities and may offer opportunities for the sonification of data to accompany or replace visualization when contextually appropriate. While this points to exciting possibilities for interaction with ubiquitous visualization, it may also lead to another way in which users can become overwhelmed, unsure about whether they can expect to use gestures, speech, proxemics or other modalities. In particular, Elqmvist suggests to consider people's limited resources, just like memory and rendering performance, as something that needs to be respected when designing ubiquitous visualizations. Regarding this topic, Rogers sees a lot of promise in physical and tangible interfaces to support engaging and fun experiences, and looks ahead to plant-based interfaces. White notes that we are currently in a phase with lots of design possibilities, many of which will disappear when the design will coalesce around some key interactions that work well.

9.8 SCENARIOS FOR UBIQUITOUS VISUALIZATION

We envisioned a few scenarios for ubiquitous visualization based on conversations at our Dagstuhl seminar “Mobile Data Visualization” as well as the interviews we conducted for this chapter.

Personal informatics is a major theme where information about an individual is crucial to the individual and is provided in a contextualized form. The *Quantified Self* movement consists of individuals who are passionate about collecting high-resolution data about their health, exercise, energy consumption, shopping habits, and so on. For example, a device such as a smartwatch not only captures the data regarding an individual’s health, but also allows them to explore it either on the watch itself or on a mobile phone. Mundane tasks such as brushing your teeth, drinking coffee, or shopping could be scenarios in which we may see innovations with respect to ubiquitous visualization. Rather than experiencing visual representations only on a watch/phone, we may see representations on a toothbrush, or a coffee cup, or the handle of a shopping cart. Here one may experience “serendipitous decision-making” rather than conduct detailed analytics that would be performed on a desktop or in a collaborative setting.

We believe that mobile sensors and devices will play a big role in the **retail and sales** sectors. We may see actuated store shelves [99] as well as “smart” stores that may guide customers to various parts of the store based on real-time sales data. Rogers’ lambent shopping handle is an example where users can see information about the “distance” a food item has traveled before it reached the supermarket.

Public and private transportation will continue to see situated visualizations for the driver and passengers alike. They may be used to inform the driver and the passengers about the current state of the vehicle and its surroundings. In addition to the standard data on a dashboard of a car, modern cars convey the estimated amount of miles that can be driven on the current level of gas in the tank/charge on the vehicle. Future displays in an automobile will continue to get better and use a variety of sensors (distance, luminosity, acoustic, etc.) to better inform the driver about vehicles, pedestrians, and other situations that the driver may not have noticed. As a difference to mobile visualization as we know it, future traffic scenarios will increasingly involve display functionality integrated into traffic infrastructure and vehicles, but not just shown on mobile devices. We believe that displays will even be integrated into the sidewalk to provide traffic flow information for cyclists and pedestrians as a means of surfacing data in our environments.

Our vision of the future of ubiquitous visualization includes a transformation in the field of **healthcare**, where patients and medical professionals alike will have situated access to all relevant information on mobile applications for rapid decision making. Medicine and healthcare will be completely transformed in the near future due to mobile and ubiquitous visualization. Surgeons and other medical staff will be able to gain deeper insight into the patient's current health conditions before, after, and as they are conducting the surgery – either through augmented reality or through other handheld devices for diagnosis (for example, overlaying CT scan data on patients) and treatment (for example, utilizing adaptive visualizations for post-surgery medication). We envision mobile interfaces to consider multifaceted health data that can be interacted with using multimodal input (touch, voice, force, etc.) and to communicate it via visualizations and even non-visual renderings to other stakeholders regardless of their physical location, a vision also called the Tactile Internet [28].

Cyber-Physical Systems where data is being collected from a variety of entities such as a train or a bus, a toll booth, a water fountain, a trash can, and so on can be visualized seamlessly on situated devices and mobile displays. Some insights from analyzing this data could be conveyed to a casual bystander waiting for the next train or walking past a display in a store to increase their awareness of current urban issues and empower their decision-making.

Crisis management is an overarching theme as a future application domain for ubiquitous visualization. Individuals in a geographic region could be notified on their smart watches/phones/glasses, information about evacuation routes or communicating urgent messages (similar to the Amber alert system in North America that is used to request the public for assistance with finding a missing child.) Car emoji displays (shown on the rear dash) such as the Mojipic[9] could be used to provide helpful information to vehicles behind you in such a scenario. Mobile devices could also be used to increase situational awareness for **improved safety** in personal or public emergency or even military situations. Individual safety can be increased for students on campus by being informed about the location of police officers nearby or zones to avoid. In the future, we may also see personal drones as an informative or collaborative device that can serve to communicate a message to nearby individuals. One such scenario could be when a disabled or elderly person needs **assistance** and the display on the drone can communicate that to the nearby individuals through sound, light, or even notifications on their devices. Drones may also be used in the future for large-scale data collection as well as data aggregation such as in the example in Willett's interview where thousands of drones may go out into a field and provide an overview of specific attributes such as soil moisture.

Construction and **Maintenance** are domains in which we will see larger use of ubiquitous visualization that can provide contextual information on demand to technicians and workers. The mobile device can overlay information onto machinery with level-of-detail representations being displayed on a mobile device or augmented reality glass (creating a so-called digital twin of a physical environments [68]). These systems could also take into account proxemics, for example to show more detailed information as the technician gets closer to some equipment or section of a building.

Communicating emotions and feelings in private and public settings through shape and/or color-changing fabrics could be a reality in the future. In private settings with your family or friends, an individual's smart clothes could communicate happiness,

[9]https://mojipic.co/

sadness, anger, and so on through a pattern of the fabric. A shape-changing collar or buttons that grow/shrink in size based on a specific emotion or physical condition (heart rate/blood pressure/blood sugar parameters) would also be a way to provide subtle non-verbal cues.

In a public setting such as a dance club, an individual's clothing may have embroidered displays into the fabric that all work together to communicate their current mood, mental state, or physical state (tired, alcohol consumed, heart rate) to the people around them. While less futuristic, a watch band or other jewellery might be illuminated to communicate feelings or information [57]. There may also be subtle ways of communicating interest in other people at the club through color- or shape-changing fabric.

9.9 REVISITING THE DIMENSIONS OF MOBILE VISUALIZATION

In Chapter 1 the dimensions of mobile data visualizations were introduced as a way to describing existing core cases of mobile visualization, from charts on smartwatches read while running to shared tablet displays used in the field. The experts interviewed have opened up the design space for visualization moving from mobile to ubiquitous, and in this section we will revisit the dimensions to investigate if they require extensions to include the additional factors.

9.9.1 Reflecting on the Dimensions of Mobile Visualization from our Interviews

The first dimension of mobile visualization is the **data display mobility**. Our experts discussed a range of technologies across all levels of display mobility. Willett proposed that the fastest way to achieve a vision of ubiquitous visualization is from the (relatively) *fixed* ecosystem of in-vehicle screens. This configuration is similar to the edge case of in-cabin displays on aircraft, which are fixed relative to the viewer, but moving through the external world. Rogers suggested similar embedded technologies fixed in the world around us, such as data displayed on coffee shop walls, and expanded out to *movable* displays embedded in shopping cart handles, or even futuristic ideas of data display using plants. White focused on *wearable* see-through displays to augment the world around us with data. And Elmqvist reflected on drones used to display data with *viewer-independent movement*. The typical mobile visualization technology, the *carryable* phone, was the least discussed means to achieving the vision of ubiquitous visualization. Each expert shared the vision that ubiquity means being free to interact with the world around us. Rogers clearly stated, "everyone is looking down at their phones [...] we can design ways to get them to "look up, look out."

The second dimension is the **physical display size**, running from *pixel-sized* to *wall-sized*. This dimension did arise in the interviews, including Willett's discussion of single-bit LEDs for biking and parking to White's smart glasses, and Rogers' suggestion of large-scale displays of data in coffee shops or public squares. Willett frames the display size dimension in relation to information density and information complexity, where information that is glanceable may often be desired in situ, and the information density and complexity could adapt to the display size, from small wearable displays to coordinated displays embedded in the environment. This relates to the edge case of micro-mobility through linked display devices, such as two tablets which can be arranged in different configurations on a tabletop, as discussed in Chapter 1. Willett's ecosystem of displays essentially extends this idea into a very large total display size made of many smaller displays in a contextually-appropriate arrangement. What this physical display size dimension from Chapter 1 does not fully cover is the use of *see-through* display technology. For example, AR glasses placed right before the eye, or AR contact lenses, may someday create complete field-of-view coverage for displaying situated data visualizations. Perhaps this calls for another dimension of **display transparency** including levels of *closed-view, video-based see-through*, and *optical see-through* displays, following the terminology of Azuma [3].

The third dimension is the **visualization's reaction to display movement**. This considers how mobile visualizations respond to movement, including direct change (e.g. GPS location data is part of the visualization) and indirect change (user movement induces heart rate which is part of the visualization). In the interviews, we heard consensus that ubiquitous visualization would primarily be situated and contextual, to the location, movement, tasks, people present, environmental factors, etc. In this way, ubiquitous visualization moves beyond responsiveness to movement toward responsiveness to many contextual cues, driven by new types of sensors such as LIDAR, and novel technologies such as fabric-based interfaces [67, 56]. We also heard that it is not only the display movement, but also the **data movement** that may characterize ubiquitous visualization. Data may be *fixed to a single device* in the base case. When the user, rather than the device, is the central factor in a visualization system, the data and visualization views of it can be *linked to the user*, moving from display to display in an augmented environment, or with the user in a wearable system. Data may also *move with the task* across multiple users as needed. As Elmqvist posits, it may be possible to have different levels of sophistication in the various 'nodes' of the device ecosystem, with some devices being compute-heavy (e.g. laptops) while others are displays for the end result (e.g. smartwatches).

The fourth dimension is the **visualization interaction complexity** spanning from *passive interaction* to *highly interactive.* Ubiquitous visualizations may similarly run the gamut of interactive complexities, from passive views of situated data in the environment to highly interactive scenarios responding to multimodal inputs such as speech, mid-air gestures, and interactions on peripheral devices. Furthermore, the system response in ubiquitous scenarios may more often be non-visual (e.g. speech, directional audio, haptics) than in typical mobile visualizations. The vision for ubiquitous visualization interaction in our discussions called to mind Elmqvist's *fluid interaction* [27] — seamless interaction across modalities which does not interrupt the cognitive flow or process of analysis.

The interaction focus in the interviews was on the modality of interaction, and the use of novel technology to enable interaction, such as Willett's and Elmqvist's mention of proxemics on the passive end of the dimension, and ultrasound haptics enabling fluid interaction in the other extreme. Rogers works a lot with tangible and physical interaction to explore the design of interfaces that are attractive, aesthetic, functional and engage people. She thinks the next generation of interfaces will be physical and tangible and looked ahead to plant-based interfaces that could be physical, change their form and appearance (e.g. by glowing). White raised the need for software toolkits that bridge technologies so that we can move beyond one-off prototypes.

The fifth dimension is the **data source** which spans across *captured, connected, and preloaded data.* As we move toward ubiquitous visualization all the scenarios discussed in the interviews were contextual. Contextual awareness enables the situated analytics workflows envisioned in the interviews with White and Willett. This necessarily requires at least some capturing of data such as location, orientation, or other sensor data feeds. Mobile visualization aims to bring data with the user wherever needed; ubiquitous visualization brings the right data to the user at the right time, in relation to the physical, social, and environmental context. As such, it is likely that ubiquitous visualizations will almost always fall under the *combination* level of the data source dimension, combining onboard data with cloud-connected and sensor data. However, our interviewees also mention that contextual adaption is tricky. Rogers stated that we "need to be careful with contextual approaches – is it to bring the right data up at the right time? I haven't seen that many useful adaptive interfaces. [. . .] Very simple visualizations sometimes are the best."

The sixth dimension is the **intended viewing timespan**, from *glanceable* visualizations to long-term use of *hours or more.* Willett's vision of instrumented multi-screen car environments is actually an extension of the sub-second glance example of an in-car GPS panel discussed in Chapter 1. Like mobile visualizations, ubiquitous visualization will likely span the full spectrum of this dimension. In ubiquitous visualization scenarios, one can imagine glancing at a rich visual notification displayed in the glasses White predicts will become popular, or conducting a deeper analysis of data such as in White's augmented botany field guides [94, 98].

The final dimension is the **intended sharing**, from *personal use* to *general public.* In ubiquitous visualization scenarios, the intended sharing may be highly linked to the display technology, as some technologies such as glasses are personal and viewable by only one person, while others such as displays in the shopping mall are within public view. As Rogers alluded to, the uses of these displays for data display will have to consider their social context. Both Rogers and White suggest that public sharing can become more social, engaging people with each other through data, rather than passive viewing of large displays. Ubiquitous visualization could also be used by *a few people* in groups, for example, field researchers having a first-person view on the same dataset as they roam a forest, or industrial workers seeing personalized data overlays in a factory setting. Ubiquitous visualizations in the environment could be used by *larger groups* in shared workplaces, such as ambient hallway visualizations, or by the *general public*, such as on displays of subway platforms or, as Rogers suggests, in a busy public space such as Picadilly Circus.

The vision for ubiquitous visualization suggests *new levels of this dimension.* First, *linked personal views* in which users have a personal view on a partially or fully shared dataset. These views may be customized to the user's point of view, role, preferences, and interest. For example, two people may be looking at a visualization on their private displays, using preferred color schemes and representation types, but interaction could provide linked highlighting. Ubiquitous technologies may also allow for *hybrid sharing* in which part of the data is shared, e.g. on a wall display, and part of the data is private or user-specific, e.g. overlays displayed in AR glasses. Hybrid sharing could also be achieved through public displays of data in which the included data or the design of the representation is only understandable by a subset of the viewers who possess specialized knowledge.

9.9.2 Expanding the Dimensions with Context

The originally discussed *dimensions of mobile data visualization* embedded contextual awareness within several related dimensions, including *visualization's reaction to display movement*, *data movement*, and *data source*. A common trend in our interviews was that ubiquitous visualization would be more situated within people's activities and settings. We also discussed opportunities for visualizations to respond and adapt to the changing context. While mobile visualizations may take into account the context through the use of motion sensors and GPS location, or may be personalized to the user, this dimension may achieve more variety in ubiquitous scenarios. We can imagine reframing the contextual dependency into a specific additional dimension for the **level of context-awareness** of the visualization [23]. As a first step, based on our four interviews, we propose that levels of this dimension could be:

non-context-aware The visualization does not change with context.

user context-aware The visualization responds to the user's transient physical or mental state, preferences, or long standing traits.

physically context-aware The visualization is specific to the physical, temporal, or environmental context.

socially context-aware The visualization responds to the number of people in the environment, their social and physical interrelations, tasks, and roles.

combination The visualization has aspects of a combination of user, physical, and social contextualization.

In addition to the type of context awareness, the **response to context** can also vary between passive awareness (which merely suggests and requires user confirmation) and active awareness (where the interface adjustments are autonomously applied) [18]. For example, a passive user context-aware visualization may emphasize the heart rate chart button if user exercise is detected, while an active contextual response would be to simply show the chart directly on the home screen without first prompting. There are interesting considerations and trade-offs to consider between these approaches to embedding context awareness, including interface stability, predictability, and the level of user control [9].

Note that unlike the original dimensions discussed in Chapter 1, a specific instantiation of a ubiquitous visualization could have multiple levels of context awareness through *combination*. For example, an augmented reality visualization for jogging could be responsive to the *physical context* (GPS directions, local traffic), the *user* *context* (heart rate, breathing), and the *social context* (location and status of runners accompanying the user). Such a head's up visualization would allow the user to safely challenge themselves to reach exercise goals while adapting to changing environmental conditions and staying in sync with their friends.

However, as a caveat, we want to emphasize that delineating "context" in this way is challenging and has long been discussed in the ubiquitous computing community. Dourish noted that the ubiquitous computing literature has mostly looked at context as a representational problem (instead of an interactional problem), and that the sociological critique on context-awareness is that the kind of thing that can be modeled or computationally represented is *not* what context is [25]. According to Taylor, Dourish instead argues that "context is something that is continuously being made and dependent to a large degree on the ever-changing relations between people and the resources they bring to bear in everyday settings" [86]. Similarly, Greenberg argued that context is not a stable set of contextual states, but rather a dynamically evolving situation-dependent construct [31]. Indeed, most successful examples of context-awareness have been confined to quite specific, predictable and low-risk interactions (e.g. location-aware searches to find the local Starbucks, or mobile displays that automatically rotate to portrait or landscape mode depending on how they are held [39]). As mentioned above, our interviewee Yvonne Rogers mentioned that one needs to be careful with contextually-aware approaches.

Perhaps the challenge for ubiquitous visualization research is instead to identify the specific and reliably predictable interactions in which data visualizations can be made incredibly useful by being contextually relevant to the task and setting at hand (e.g. White's example of medical applications to visualize a patient's veins on their arm to support blood extractions), rather than attempting to (automatically) adapt to every possible situation.

9.10 CONCLUSION

In this chapter, we looked ahead to the future of mobile visualization. We anticipate a change from what we describe in this book as mobile visualization towards ubiquitous visualization: Data visualizations will be available everywhere and at any time using a variety of emerging technologies to display and interact with data to support people's activities in a variety of settings. To better understand this emerging topic, we reported on interviews with four renowned researchers who have explored data visualization using new technologies and in new settings in their work. We extracted recurring themes from these interviews to highlight opportunities and challenges in moving towards ubiquitous data visualization. We also discussed envisioning scenarios for ubiquitous visualization and reflect on how moving to ubiquitous visualization will impact the dimensions for mobile data visualization that were identified in Chapter 1. Overall, we hope this chapter provides insights into this exciting emerging research direction that aims at achieving ever-more available and contextually situated data visualizations that fit into people's lives.

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