CHAPTER 1

Reflections on Ubiquitous Visualization

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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.

1.1 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 [6]. In addition to enhanced display power, we are also seeing a revitalization and application of multisensory 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 eluded 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 1.2). 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 1.3, 1.4, 1.6, 1.5). This is followed by reflecting and discussing overarching and important themes we identified across the interviews (Section 1.7). 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 1.8). 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 1.9).

1.2 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, 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.

1.3 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." Willett 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[1]. 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, eas-

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

ier, and more accessible than 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. We asked whether he sees his framework as a conceptual framework to aid design: "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 autographical 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 [94] 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 includes 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?

Willett replies: "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 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".

1.4 NIKLAS ELMQVIST ON UBIQUITOUS ANALYTICS

Niklas Elmqvist is a full professor in the iSchool (College of Information Studies) and Director of the 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 googles. "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 [5]. "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 [7], and more recently Vistrates [6]. 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[2] and Vega[3], 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

[2] Data-Driven Documents: https://d3js.org/
[3] 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 [6], 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'[4], or Bongshin Lee's and colleagues' Charticulator[5]. "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

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

[5] 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.