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## CHAPTER 5

# Characterizing Glanceable Visualizations: From Perception to Behavior Change

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WE detail and illustrate glanceability as a crucial requirement for several types of mobile visualizations. For example, in a difficult terrain, a runner can only check a smartwatch for elevation or heart rate data for a few hundred milliseconds before the eyes need to refocus on the trail ahead. Such quick information needs differ from those in traditional visualizations that are meant for deep analysis and interaction with possibly large and complex datasets. Visualizations designed for quick information needs are described under a variety of terms in the literature such as glanceable visualizations, glanceable displays, peripheral displays, ambient visualizations, or sometimes as forms of casual visualizations. To clarify how glanceability is used in the field of Visualization, we discuss these related terms with respect to visualization concepts, drawing from not only Visualization but also, Vision Sciences, Human-Computer Interaction, and Ubiquitous Computing, revealing how the use of the term *glanceable* differs in these communities. Drawing from these different perspectives, we discuss specific values for glanceable mobile visualizations: presence & accessibility, simplicity & understandability, as well as suitability & purposefulness. Based on these values, we explore different evaluation methodologies, ranging from lab studies, to online experiments, to evaluation in the field and conclude with a discussion of open challenges in the design of future glanceable mobile visualizations.

## 5.1 INTRODUCTION AND CONTEXT

*Anne is on her way out of the house. While brushing her teeth she turns on her smartphone's screen and glances at the weather widget to decide if she needs a raincoat today. In the car she turns on her smartphone's GPS navigation system and gets going. While driving she looks at the screen for traffic updates. At work she attends a meeting but frequently checks her smartphone's notification light to see if she received an important message she has been expecting. During her lunch break she goes running and, while moving, glances at her smartwatch to see which distance she has already covered and whether her current pace is in-line with her training goal.*

The purpose of this chapter is to take a deeper look at the topic of glanceable visualizations integrating knowledge from multiple domains: the Vision Sciences, Visualization, Human-Computer Interaction, and Ubiquitous Computing. With this deeper look we want to establish a source of references and inspiration for more research in this important research direction. In the context of this chapter we refer to a "visualization" as a mapping from data to a visual representation. The Vision Sciences often researches simple data mappings while the Visualization community is often interested in establishing combinations of complex multi-encodings. A "visualization" in Ubiquitous Computing research does not need to be a graph or proportional drawing of data, it can take the form of a moving object (such as the movement of a dangling string, or changing fountain height), an abstraction (such as a garden representing physical activity), or a change in color could indicate a change in data.

As can be seen in the mock-scenario above, mobile devices and their visualizations are often needed as part of tasks with quick information needs. These quick information needs require someone to switch attention from a primary task to briefly attend to an information display as input on how to further continue with the primary task. For example, for someone driving to work, paying attention to the road is a primary task. Yet, sometimes quick glances to the car's GPS are necessary. The longer these glances are, the longer the primary task is disrupted resulting in potentially severe consequences.

In the scenario above, Ann performs her secondary tasks with different mobile devices—her smartphone and smartwatch. These mobile devices are often used on-the-go making it desirable that a person can perceive visualizations depicted on them at a glance. This new context leads to new challenges that traditional visualizations were not designed for; for example, not only the limited availability of time for inspection (usually just a few seconds or less), the context of use while in locomotion, the different focus of attention (as a secondary task) but also the smaller device size especially for smartwatches. Therefore, a new research challenge we call *glanceable visualizations* has evolved in recent years. Interestingly, despite the importance of glanceable visualizations we still know little about how to best design and evaluate visualizations for quick information needs.

## 5.2 PERSPECTIVES ON GLANCEABILITY

Several research fields have created and studied displays that are meant to be looked at only for a short amount of time. Within each of these disciplines, different terms and time frames have emerged for referring to these types of displays and the types of interactions that people have with them: from the Vision Sciences, which investigate the temporal limits of vision, to Visualization, which is regularly concerned with instant perception of data characteristics, to the field of Ubiquitous Computing, in which researchers use glanceable visualizations to provoke awareness and behavior change. In addition, the goals and implementations of glanceable visualizations, as well as the methods for evaluating their success vary in these domains. Visualization focuses on promoting insights and understanding from datasets with research ranging from low-level perception of specific data encodings, such as length of lines versus area size, to more encompassing notions of higher-level thinking with visualization. Glanceable visualizations have so far received little attention in the Visualization community with much of its history having been focused on work-related in-depth data analysis. In the Ubiquitous Computing domain the availability and understanding of information is considered a prerequisite. Here, research specifically focuses on the effect of technology on people's awareness, decision making, or behaviors.

Due to these different goals, we found a range of time scales researchers consider in these domains. Figure 5.1 shows these time scales: the Vision Science literature

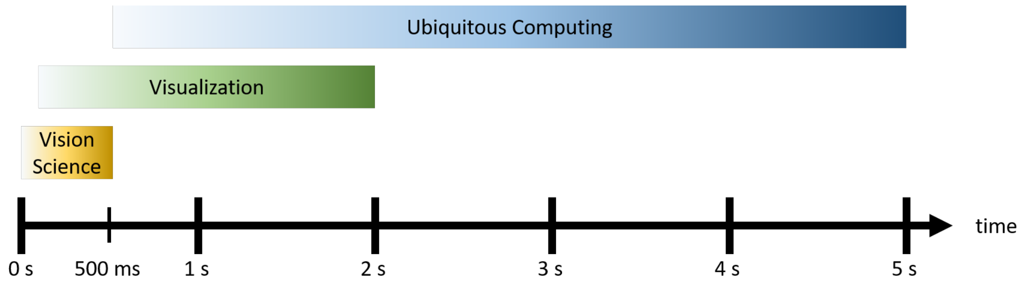


Figure 5.1: Different time scales of glanceability depending on the domain: Vision Science (50–500 ms), Visualization, and Ubiquitous Computing (500 ms–5s).

mentions time scales between 50–500 milliseconds [31], whereas the Visualization literature has been using the term *glance* for viewing times of up to 2 seconds [9]. The field of Ubiquitous Computing, as first envisioned by Weiser [56], saw computing existing in the world. As people went about their days, they would notice information ambiently displayed in the environment, understand the implications for their own actions, and act on it. This process of noticing information, understanding it, and acting on it, can take up to five seconds [26] and acting on this information can lead to short-term changes in behavior (e.g., pulling into a parking spot that has a green light) or long-term ones (e.g., increasing daily step count as a result of a wrist-worn visualization). In the following sections, we discuss where these different time scales come from based on related work that defines typical types, tasks, and goals of each individual domain.

### 5.2.1 Glanceability in Vision Science

Questions regarding a *glance* or the temporal limits of human vision—"the timescale on which the machinery of perception operates" [31]—drive research in the Vision Sciences, and researchers have invested careers conducting experiments to answer theses questions.

Holcombe [31] summarizes the results of these experiments and concludes that there are two groups of temporal limits of vision: fast and slow visual judgments. However, this phenomenon does not mean that we see quickly, but means that we "see things that occupy fast timescales." The first group consists of visual judgments that occur with up to 50 Hz (20 ms), such as flicker perception, perception of motion direction, or certain color perception. The second, slow group, concerns rates from 10 Hz (50 ms) up to around 3 Hz (166 ms) and consists of visual judgments such as the detection of changes in speed, direction of moving objects or word perception.

Some past work has offered insight on how the notion of attention relates to quick perception of stimuli. Rapid and parallel low-level visual processes (also referred to as pre-attentive processing) of unique visual properties (e.g., color hue, length, size, curvature) lead to a "pop out" effect. People can detect targets, boundaries, or regions as well as count and estimate the number of elements [29]. These capabilities allow people to rapidly detect whether an orange circle is present among many blue circles (cf. Figure 5.2a). Some of these visual properties are asymmetric. For example, people cannot quickly find a horizontal line among sloped lines (cf. Figure 5.2b), while they can find a sloped line among horizontal lines (cf. Figure 5.2c). Seminal work by Treisman et al. [53, 54, 55] studied these unique visual properties. Treisman and Gelade [55] described a feature integration theory, in which simple basic features (i.e., feature maps) allow parallel processing in an early stage of visual processing. If multiple of these features are present in a stimulus at the same time, conjunction or serial search is needed (e.g., detection of an orange circle in a group of orange squares and blue circles, cf. Figure 5.2d). However, some conjunction tasks involving motion, depth, color, and orientation have been shown to be processed in parallel [59] (cf. Figure 5.2e).

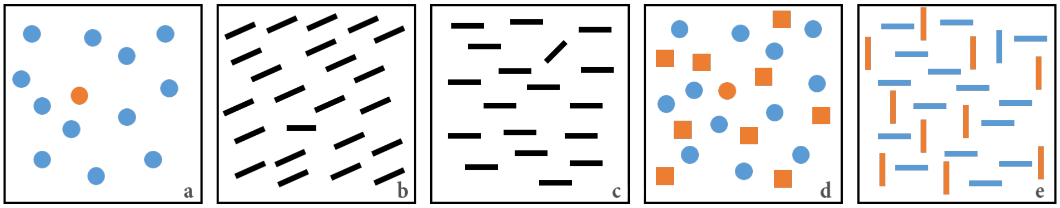


Figure 5.2: Parallel and serial processing of stimuli. (a) An orange circle amongst blue circles can be quickly detected. (b) A horizontal line amongst sloped lines cannot be quickly detected, while (c) a sloped line amongst horizontal lines can. (d) An orange circle amongst orange squares and blue circles cannot be rapidly processed, while (e) a vertical blue line amongst horizontal blue lines and orange vertical lines can.

Several experiments by Biederman et al. [5, 6, 7, 8] also gave evidence that humans are able to digest the schema of a scene based on a single glance at it. Others have similarly studied *gist perception* to understand to which extent people can see basic information quickly, often in a single fixation. Summarizing past work in this area Jahanian et al. [34] note that people can, in viewing times of 100–300 ms, identify the category of a natural scene, say whether an object is present in an image, distinguish cities, and see colors or textures. Jahanian et al. [34] also showed that participants could perceive the category of a website within 120 ms and detect certain elements on the website.

### 5.2.2 Glanceability in Visualization

From these vision experiments we can learn that humans are able to perform specific detection tasks quickly. However, why is this important for mobile devices? In several studies, researchers found out that a large amount of usage sessions on smartphones and smartwatches only lasted several seconds [3, 20], much longer than the timespans considered at a glance in the Vision Sciences, but still short enough to ask oneself how much information a person can perceive and act on.

Therefore, it is interesting to find out how much information can be conveyed using visualizations within such short glances, especially when trying to communicate data for quick information needs. For defining what glanceability in the Visualization domain means, we first have to understand the context such visualizations are used in. The ubiquity of smartphones and smartwatches has made it obvious that the use of visualization is not restricted to the office anymore. Visualizations are nowadays present everywhere, at home, in the office, and outside, and they can show all kinds of work-related or personal data. Traditional visualizations in the office or at home are typically used as a primary task to fulfill an information need such as finding out which activities are risky during a pandemic and planning a safe exercise routine. On mobile devices, however, reading a visualization is often not the primary task anymore. For example, a person might be running outside and while running they quickly check their fitness bracelet to get information about their current heart rate or speed. These two examples show, not only, differences in the amount of potential attention to and engagement with a visualization, but the different usage time scales. In the mobile example, a runner only shortly focuses on a glanceable visualization on their smartwatch to see their step count, whereas with a traditional visualization a person spends more time to investigate and understand a visualization depicting information about a complex problem, such as, for example, the current data available on the Corona Virus.

This notion of using visualizations to quickly communicate data has in the past been considered in the context of ambient (non-mobile) visualizations. In this context, researchers were interested in how to integrate more data into ones' life without disrupting a person's primary task. Miller and Stasko [40] called this *peripheral awareness information*: "data that is not absolutely essential to people and their work or tasks." In an attempt to summarize and define what ambient versus peripheral information systems are, Pousman and Stasko [43] investigated the related work and provided a definition as well as taxonomy for ambient information visualizations. In a later paper, Pousman et al. [44] go one step further and define *casual information visualization*, with ambient information systems belonging to this new group of information visualization systems. However, specific viewing timespans and how much information people could retain during quick glances at ambient displays was not the focus of dedicated visualization studies.

More recently, researchers in the Human-Computer Interaction and Visualization communities worked on ways to help people better collect personal data and gain personal insights. Called *Personal Informatics*, this field of research deals with understanding people's data tracking needs and usage to design and develop novel self-tracking technologies for a variety of contexts (e.g., food, sleep, productivity, physical activity). This field shares with the Visualization community the goal of making it easy for people to better understand their own data and communicate personal insights, which often are captured on mobile devices due to their omnipresent nature and powerful sensing capabilities. As such, researchers have been examining how to design effective glanceable visualizations that convey personal data on mobile devices especially for lay individuals.

In the mobile visualization context, researchers have recently started to study exact thresholds of glanceability for different chart types. Blascheck et al. [9] found that a simple data comparison task, which required participants to quickly identify the larger of two marks in a bar, donut, and radial chart, can be performed within less than 300 ms for donut and bar charts (cf. Figure 5.3). Neshati et al. [41] investigated different compression types for line charts on smartwatches. Their main focus was not to find a minimal threshold for completion time, but they did record the response time per task. For tasks involving the comparison of line chart start and endpoints the response times were in a range of 2000–3000 ms but included the time to enter an answer on the keyboard.

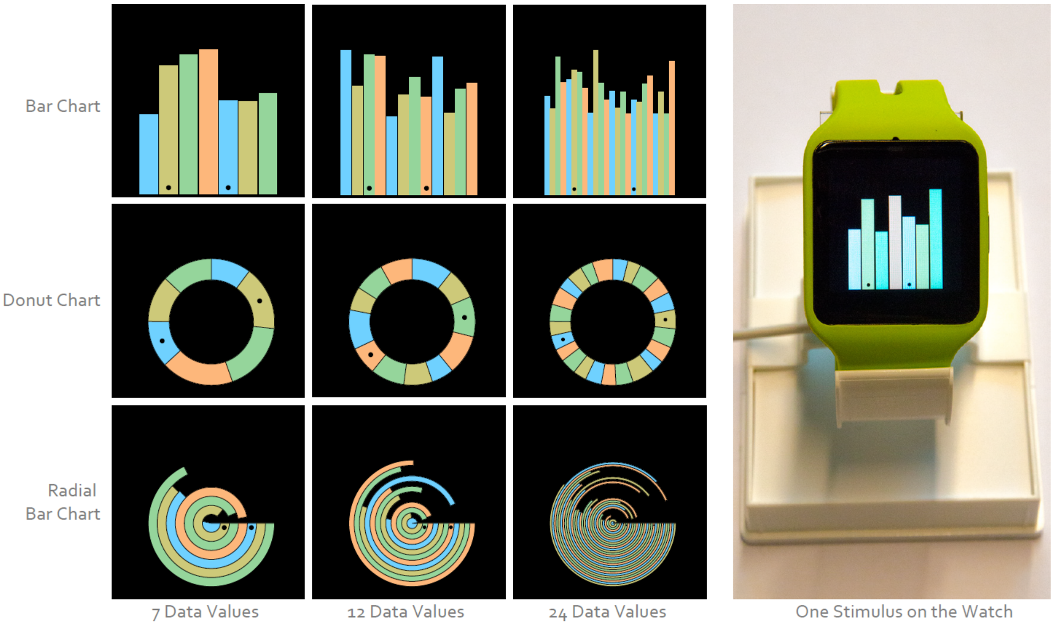


Figure 5.3: Stimuli (left) and smartwatch (right) used in a lab-study to assess glanceability of different visualizations for simple data comparison task on a smartwatch. *Image © 2019 IEEE. Reprinted, with permission, from [9]*

In summary, dedicated research on minimal perception times for visualizations on mobile devices is still in its beginning. Few studies have been carried out and this is a vast area to explore further and for which to develop dedicated design guidelines.

### 5.2.3 Glanceability in Ubiquitous Computing

Since its inception, the field of Ubiquitous Computing has been interested in systems that present information as a part of a person's environment. Visualization are often meant to be sensed in the periphery of one's environment. In 1996, Mark Weiser and John Seely Brown at Xerox PARC [57] described the periphery as "what we are attuned to without attending to explicitly" and the goal of the peripheral displays they created was to allow people to have a subconscious awareness of a variety of information and to move particular pieces of information from the periphery to the center of their attention and back again when that information was particularly salient and relevant. They described this *calm* technology as allowing people to be aware of many things without overburdening them with needing to explicitly attend to differences in graphs or data tables to gain information.

This vision was extended by Hiroshi Ishii's group at the MIT Media Lab, using the term *ambient displays*, in 1998 [58]. They defined these new types of displays as systems in which "information is moved off the screen into the physical environment, manifesting itself as subtle changes in form, movement, sound, color, smell, temperature, or light" [58].

These two projects kicked off decades of research and commercial products focused on creating peripheral or ambient displays that provided information to people in a variety of abstract ways. Early systems in this space allowed people to learn about network activity via a dangling string (and decide when to print) [57], to hear ambient sound of another location [58], to have an umbrella that glows when you need to take it [45], or to see a glowing orb that indicates when your friends are watching television [28]. Many examples of this type of research can be found in David Rose's book, Enchanted Objects [49].

Peripheral or ambient displays typically have a goal of guiding behavior leading to focused behavior change. The first goal of one of these displays is to make a person aware of something—that it will rain [45], that their partner is on their way home from work [36], that they are behind on their step count for the day [17], etc. Once a person is aware of this information, the goal is that they then are able to make a targeted behavior change given that new data. For example, they might take the umbrella with them, start preparing dinner, or go for a walk in the cases mentioned.

Most notably, with these types of systems a person should not have to explicitly look at and attend to the display. However, this information should be something that is noticed as a part of living one's ordinary life and traversing the spaces where one lives and works, with changes in lighting, color, sound, or smell naturally translating into gained awareness.

Many times, these visualizations end up being quite abstract. For example, the InfoCanvas system [52] allowed graphics that conveyed information to be placed onto a framed photo. Fogarty et al.'s [21] Kadinsky system generated even more artistic representations of data made for a digital canvas. In these systems, it is often not efficiency or accuracy of conveying data that is the most important but rather the experience of living with these data displays for extended periods of time and their utility in daily life that is the most important aspect to measure.

While peripheral or ambient displays are meant to catch a person's attention from the periphery, a new field of *glanceable* displays has emerged with a goal of providing information quickly to a person who has chosen to give the display their explicit attention for a brief amount of time. These systems have used a variety of techniques to display information in a rapidly understandable fashion. In the Ubiquitous Computing domain, these displays most commonly borrowed abstractions from ambient devices, but adapted the lessons learned from physical devices for use on a screen [38]. Color, icons, graphical representations, or changes in size were used to convey information at a glance.

The key difference between a peripheral or ambient display and a glanceable one is a person's attention. With glanceable visualizations, a person intentionally looks at the screen to receive information, instead of it being delivered without explicit attention in the periphery. This makes glanceable visualizations a more purposeful instrument, much like a pilot checking an instrument panel to make sure nothing has gone wrong.

Matthews et al. [39] explored many types of glanceable displays in detail, defining several key terms. While the actual time looking at a display may be small (on average 34 ms in their work), the *peripheral processing time* that it took a person to understand and internalize what they saw often took as much as two seconds (mean = 1,931 ms). They also found that text was the “fastest and most accurate to interpret” representation, compared to a variety of abstractions (note that Plaue et al. [42] find that graphical abstractions are more salient to remember later on). Because the goal is to inspire behavior change, time for contemplation and internalization of the results is critical for people to decide on a change to their actions.

### 5.2.4 Summary

These past sections have shown that there are contrasting perspectives what *glanceable* means across disciplines and Figure 5.1 shows this continuum of time scales the different disciplines consider a *glance*. This reflects the differing goals of research projects within these research communities.

As discussed in the previous paragraphs, Vision Science looks at temporal time scales of 50 Hz – 500 ms to be considered a glance. The Visualization community, which often takes inspiration from Vision Science has been considering similar times closer to the upper end of those looked at in Vision Science [9]. In Visualization, the goal is typically to identify differences in data values in artificially created scenes, for example, asking people to determine if one bar is bigger or smaller than another. So far, research on glanceable visualizations has not considered people’s understanding of what the data represents and what it implies. Therefore, it has often only been the time needed for perception that is measured, not time to understand the data and especially not for realizing implications to one’s life. These questions, are however interesting to Visualization researchers and here the community begins to intersect with Ubiquitous Computing. The Ubiquitous Computing literature often has the goal of understanding how various visualizations affect people’s awareness, decision making, or behavior and if people can understand the data within a visualization and what that means for their lives. Therefore, this literature often considers viewing interactions up to five seconds or more as glanceable [26], as this includes the time that a person takes to process this information in their brain and understand if there is any behavior that should be changed. Therefore, for the remainder of this chapter, when we refer to a glanceable visualization we take a broad view and use viewing times between 20 ms – 5 s to describe a *glance*, depending on the goal of a person.

## 5.3 CHARACTERISTICS OF GLANCEABLE VISUALIZATIONS

As the previous section has shown, the different communities have different takes on what *glanceability* means. Here, we move away from trying to understand glanceability in terms of perception times and instead try to summarize the characteristics that could make visualizations glanceable. Specifically, we see three categories of characteristics:

First, the visualizations and their hosting displays must be visible to one or more people or be able to attract their attention, i. e., they are *present & accessible*. Second, people must be able to process the shown visualization at a glance, therefore, a visualization must be designed with *simplicity & understandability* in mind. Finally, glanceable visualizations are meant to support people in everyday life by informing short-term decisions or enabling long-term behavior changes. In consequence, it is important to reflect about the *suitability & purpose* of a glanceable visualization for a given goal of a person.

### 5.3.1 Presence & Access

The main goal for glanceable visualizations is to quickly provide information to an individual when the person switches their attention to it, either on purpose or based on peripheral stimuli. Therefore, the represented content must be present and accessible, or in other words, ready to be consumed. As a precondition for presence & access, the display or device should be placed in a way that only a minimal eye movement is required to glance at the content. Consider a smartphone lying on a table or mounted in a car: here, the person can quickly look at the device without any further movements or interactions. In contrast, when the smartphone is in a pocket and must be taken out first, a primary task might get too interrupted for the device to be considered glanceable. In contrast, smartwatches or fitness trackers require a small arm rotation to look at the display, but this movement only takes up a minimal amount of time and effort. These minimal body movements, rotating wrist or head, are a simplistic, natural type of interaction and differ from the typical conception of *interaction* in the Visualization or Human-Computer Interaction domain, for example, as a sequence of mouse or touch events. As such, the context of use of a display can have a large impact on whether or not it can adequately host glanceable visualizations.

For the visualizations themselves, interactions should be short-term and most often passive [51, p.141]. People should not be required to select, activate, or manipulate shown content but to primarily look at it. However, to enable looking, deliberate movements to see the content might be involved, such as rotating the wrist with a smartwatch, looking up at a public display, or fixating a certain area of the phone.

For the activities that involve quick information needs, explicitly glancing at a visualization can be considered as a part of a persons' primary task, for example, confirming the current pace while running, looking at turn-by-turn instructions while driving, or checking the progress toward a daily goal. In most cases, one specific piece of information is of interest and looked at, however, other information might be shown as well, for example, running distance, surroundings during navigation, or progresses toward additional goals. People can still perceive these additional information peripherally and incorporate them for spontaneous change of plans.

As an example encapsulating the characteristics of presence and access to content, consider the setup presented by Klamka et al. [37]. The authors proposed to extend smartwatches with interactive wrist bands that come with embedded displays (Figure 5.4). Such a setup improves the glanceability of smartwatches further, as the inward facing strap band is visible without rotating the arm. The authors propose to use this

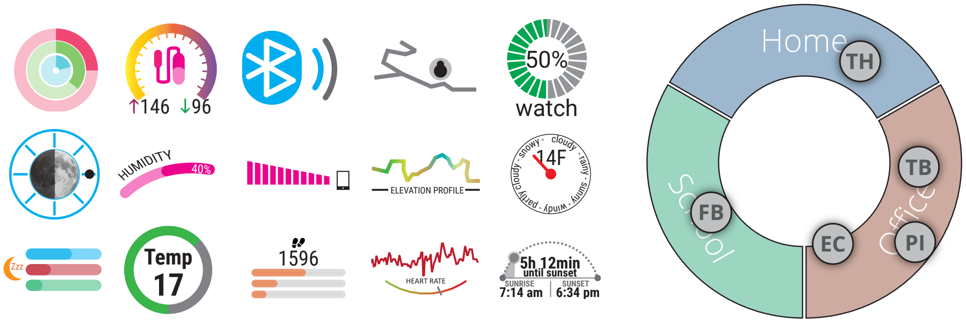
Figure 5.4: Smartwatch with additional displays embedded in the straps [37]; a person can glance at these displays without additional movements or interactions. *Images © 2020 Tom Horak and Konstantin Klamka.*

display area, for example, to show core information while running but also to show text-based notifications. The first example represents a case, in which the glanceable visualization supports a primary task, while the notifications are an example of a peripheral display. In both cases the information is provided in an unobtrusive way with only minimal eye movements being required to consume it. It is, therefore, present at an instance and easily accessible to the wearer.

### 5.3.2 Simplicity & Understandability

Another important characteristic of glanceable visualizations is the ease at which they are able to be processed. Glanceable visualizations should favor simple representations and understandability without requiring much (or any) learning. This touches on knowledge coming from Perception and Visualization research: Which chart, or representation in general, can be efficiently read? What color schemes are more effective? Which visual attributes are perceived without focused attention? For most glanceable visualizations the underlying data is likely simple (e.g., dates with a low number of attributes, a few data points), so simple chart types should be considered. These can comprise, for example, bar charts, line charts, pie charts, or donut charts, but their use should be carefully considered. Existing research on micro or word-sized visualizations [4, 25, 33] (Figure 5.5a) as well as glyph representations [10, 23] can provide further insights in how to visualize data in a compact way. Past research has shown that there might be considerable time differences with which certain tasks can be performed [9] and considerable differences in the general public's ability to understand basic charts [24].

In this context, it should also be considered *whether* a chart is required at all. In the context of running, displaying the values as numbers is currently the default case and text can be read quickly by most people. Having numbers, a runner can see the specific values and does not have to mentally map a mark to a value. Another example is the Whereabouts Clock by Sellen et al. [50] and Brown et al. [15]. As



(a) (b)

Figure 5.5: Glanceable visualizations often feature a rather simple appearance. (a) Examples of micro visualizations as found on smartwatch faces [33]. (b) Illustration of the Whereabouts Clock as proposed by Brown et al. [15].

illustrated in Figure 5.5b, the abstract locations (e.g., at home, at school, at the office) of family members are shown on a circular interface. The different locations are colored, circular segments, into which small avatars for each person are placed in. While no exact mapping is done, it is straightforward to understand the encoded information, that is, where a person currently is located. In contrast, displaying the location on a map would add more detail, but would also make it more difficult to extract the relevant information. Such simplifications and suitable abstractions are especially important as visualization literacy cannot be taken for granted [12, 13, 24]. In general, the understandability of specific representations or concepts is driven by the familiarity of a person with these or similar ones.

### 5.3.3 Suitability & Purpose

Glanceable visualizations should consider specific tasks that an individual wants to accomplish. For example, the goal can be as specific as acquiring a certain piece of information or more vague like informing a decision: Should I run faster or slower? Should I take the stairs or the elevators? Should I do some stretches in the next minutes? As a result, the chosen representation must be suitable to actually inform these tasks by providing a fitting data encoding.

For example, Amini et al. [1] conducted a design elicitation, during which designers had to provide sketches for different insight types within a smartwatch fitness application. These types comprised single values, multiple values, goal-based, comparison (other), comparison (multiple), and motivational. For goal-based insights, the proposed designs used chart-based representations showing the progress towards a goal, while for motivational insights (e.g., 5 min to go) designers relied more heavily on metaphors such as trophies or cupcakes as waiting rewards. The representations provided in Figure 5.6 are illustrating some instances of the possible designs. The exploration of Amini et al. [1] clearly indicates the dimensions of the available design space for mobile visualizations and that for a specific design the expected usage context and user goals have to be carefully considered to provide a suitable visualization. Notably,

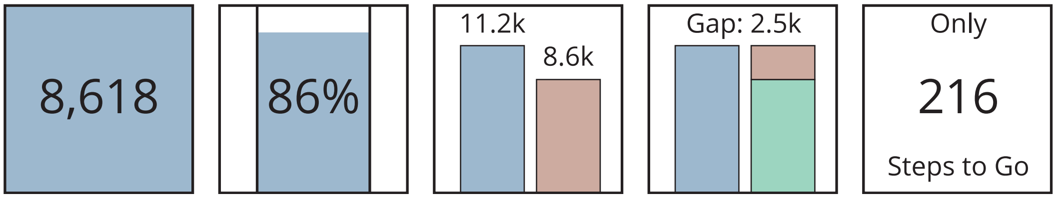


Figure 5.6: Example representations for visualizing progress towards a goal; inspired by design explorations of Amini et al. [1]. How well a specific design is suited depends on the current usage context.

which visualization design is most suited can also change within the same general context. For example, for a progress towards a goal the difference between 54 or 55% is not as relevant to a person as the difference between 99 and 100%. In consequence, this could mean that values are shown in a compact format by default, for example, *8.6k steps*, but when getting closer to a specific goal or simply a round number, the value is shown in full length (*8,618 steps*) to emphasize this small gap. By explicitly emphasizing these important differences, the visualization can better serve its purpose of motivating people in reaching their goals.

This purpose of glanceable visualizations becomes even more important when considering long term behavior changes. Representations made for this context must provide a certain appeal to be revisited over and over again. On the one hand, appeal could come from indicators that the person is making progress towards a given goal, and on the other hand from an aesthetic design that pleases the viewer. For the daily question of taking the stairs or the elevator, Rogers et al. [48] proposed an ambient installation in an office building consisting of blinking lights in the floor directing people towards the stairs, a physical presentation indicating how often people took the stairs or the elevator, and a large display with pie charts visualizing the ratio of the last days. This simple but aesthetic design caused discussions between passing persons but also seemed to lead to an increased stair usage.

As an example for a strong usage of metaphors for communicating progress, the UbiGreen tracking tool [22] encodes the weekly transportation habits of a person, and how environmentally friendly they are, as a blooming tree or a growing polar ecosystem. Because the representation is placed as an animated background screen on the mobile device, people can check the status anytime and perceive their current state; further, a rewarding detail is added to the scenery if a certain goal is reached at the end of the week. The metaphor of a growing plant (see Figure 5.7) or ecosystem also addresses an aesthetic aspiration by providing a natural looking scene instead of a technical appearance; however, this notion of aesthetics is likely to vary between different target groups and contexts.

### 5.3.4 Summary

In summary, the provided examples show that the suitability and purpose of glanceable visualizations are strongly related to simplicity and aesthetics. By providing a pleasing and easy-to-understand representation, chances are higher that people will keep

Figure 5.7: An example of a glanceable visualization on smartwatch's watch face. In this watch face app called "Sprout," the growth of the plants is mapped to the user's step count. The plants reset daily.

consuming a visualization and, consequently, may be better supported in reaching their long term goals. However, it is important to note that just because information is presented in an easy to perceive manner in the right place at the right time, it does not mean that people will necessarily act on it. The literature is full of examples of failed systems [38], in which people did not desire to change their behavior, found maintenance of devices or sensors not to be worth the effort, or did not find value in the data collected. No matter how compelling the visualization, people might still want to eat their pizza, drive their car, or do other actions that are not in their long-term best interest.

For all these characteristics, it is challenging to assess if a mobile visualization adequately satisfied its goals, especially as knowledge from multiple research disciplines is involved and comes to play. At the same time, the Visualization, Human-Computer Interaction, and Ubiquitous Computing communities have established approaches of how to evaluate various aspects of visualizations, which we discuss in the next section.

## 5.4 EVALUATION OF GLANCEABLE VISUALIZATIONS

In a systematic review of 581 visualization research papers, researchers [32] found that a visualization's effectiveness is predominantly measured by resulting images and algorithmic performance. Only recently has there been a steady increase in human subjects studies, in which researchers measure experience (e.g., reporting feedback from experts) and performance (e.g., time, error, cognitive workload). However, these traditional ways of evaluating visualizations may not be enough to capture all of the key values and uniqueness that glanceable visualizations offer, which we mentioned in the earlier sections. Glanceable visualizations are meaningfully *lived with* rather than *used* [27], and present new challenges to evaluation methods. As described in Section 5.3.1, the nature of the interaction is brief, hence the information conveyed via glanceable visualizations should be perceived in a quick and effective manner. Moreover, to evaluate simplicity and understandability of glanceable visualizations as mentioned in Section 5.3.2, we need methods that can capture people's level of comprehension, ideally with realistic datasets. Suitability and purpose (see Section 5.3.3) could be meaningfully captured in-situ over a prolonged period of time. In this section, we review how researchers have evaluated glanceable visualizations in prior work, discuss what challenges they present, and offer recommendations on evaluation methods and metrics to be used for a variety of goals. We note that in Chapter 6, broader goals and methods beyond measuring and evaluating glanceability are discussed.

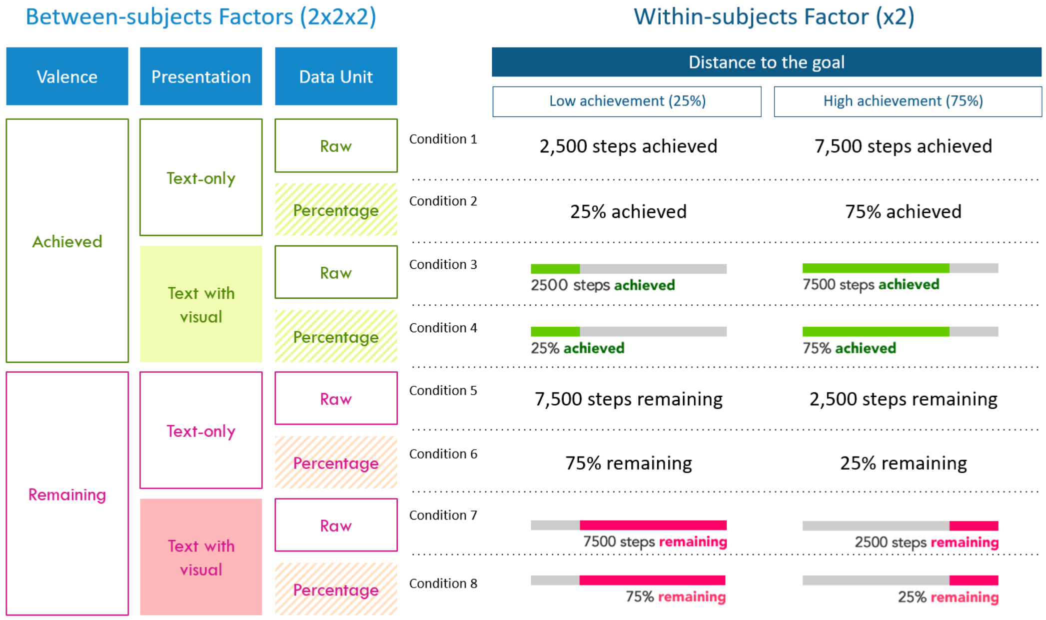
### 5.4.1 Evaluations in the Lab

In evaluating glanceable visualization, it is critical to measure the glanceability of the visualization—defined as "how quickly and easily feedback is able to convey information after one pays attention" [18]. As such, glanceability can be measured with traditional metrics such as time and accuracy through an in-lab study. Blascheck et al. [9] conducted two perception studies to assess how quickly people can perform a simple data comparison task for small-scale visualizations on a smartwatch. To evaluate glanceability, the authors designed a simple data comparison task and calculated a reading time threshold for each chart type by data size condition (cf. Figure 5.3). They found that on a smartwatch, data can be read for up to 24 data values for bar and donut charts within less than 300 ms (donut: 216 ms, bar: 285 ms). The radial chart on average had times larger than 500 ms. This study indicates that when it comes to a data comparison task, these visualizations were glanceable, although different charts offered different efficacy of glanceability. These perception studies use domain-agnostic data and do not consider people's ability to comprehend the data—that is, people can answer a question without having to understand the meaning of the data or data encoding. In Blascheck et al.'s work, the study was conducted in a lab setting, in which a smartwatch was positioned in a fixed setting and participants were not distracted with other activities. While such a setup is far from people's real-world experience with glanceable visualizations, lab studies can be a first step in determining and measuring the glanceability of visualizations in the most strict sense, as the glanceability can only be diminished in a real-world environment, in which people are exposed to a variety of distractions (e.g., light, noise, movement, and other activities).

### 5.4.2 Online Experiments

Glanceable visualizations can also be evaluated through online experiments, although the goal may be to evaluate glanceability as well as other aspects of glanceable visualization. Mechanical Turk or Prolific could be used as an online experiment platform to test graphical perception experiments, exemplified by Heer and Bostock [30]. Such crowdsourced perception experiments make it possible to recruit a large number of participants within a short time period with relatively less amount of money [11].

Going beyond testing graphical perception, online experiments can be useful in capturing other proxy measures such as behavioral intention. For example, Choe et



| Between-subjects Factors (2x2x2) | | | Within-subjects Factor (x2) | | |
|---|---|---|---|---|---|
| | | | | Distance to the goal | |
| Valence | Presentation | Data Unit | | Low achievement (25%) | High achievement (75%) |
| Achieved | Text-only | Raw | Condition 1 | 2,500 steps achieved | 7,500 steps achieved |
| | | Percentage | Condition 2 | 25% achieved | 75% achieved |
| | Text with visual | Raw | Condition 3 | 2500 steps **achieved** | 7500 steps **achieved** |
| | | Percentage | Condition 4 | 25% **achieved** | 75% **achieved** |
| Remaining | Text-only | Raw | Condition 5 | 7,500 steps remaining | 2,500 steps remaining |
| | | Percentage | Condition 6 | 75% remaining | 25% remaining |
| | Text with visual | Raw | Condition 7 | 7500 steps **remaining** | 2500 steps **remaining** |
| | | Percentage | Condition 8 | 75% **remaining** | 25% **remaining** |

Figure 5.8: An example of a mixed-methods study evaluating 16 different glanceable visualization stimuli in an online experiment [16]. Between-subjects factors were *valence*, *presentation*, and *data unit*, each of which with two levels (hence 8 conditions). Within-subjects factor was distance to the goal with two level, with the low level of goal achievement at 25% and high level of goal achievement at 75%. Participants were shown each visual stimulus with a scenario and asked to report their level of self-efficacy.

al.'s [16] study on examining the effect of different types of framing (i.e., valence, presentation type, data unit) on people's perceived behavioral intention, the researchers measured self-efficacy, a strong predictor of behavior change and maintenance [2], as an outcome variable (cf. Figure 5.8). In Kay et al.'s [35] study on evaluating uncertainty visualizations for transit predictions, the researchers measured how precisely and confidently participants extract probability information. In online experiments, researchers typically pose a hypothetical scenario (e.g., imagine you are receiving the following step count feedback on a weekday at 4:30 pm [16]; suppose you are waiting for a bus and must decide if you have enough time to get coffee before the bus arrives based on the visualization [35]). They then show a visualization or stimulus, and ask questions related to variables of interest. Similar to evaluations in the lab, a tutorial precedes the actual tasks. To ensure response quality, it is highly recommended to embed attention checks (or *gotcha*) questions to filter out participants who did not pay attention to the study materials or follow study instructions.

Although not all glanceable visualizations are mobile-specific, online experiments can be done exclusively on mobile devices when necessary, enabling participants to use their own mobile device in their natural environment. Such decisions and online experiments at large necessarily involve a trade-off between the control over potential confounds (e.g., device type, device resolution, display brightness, ambient lighting condition) and external validity (see Section 5.3. in Brehmer et al. [14] for more in-depth discussion on this topic.) Furthermore, it is hard to measure exact and trustworthy task completion times when it is unclear how or if participants were distracted from the task. Despite the trade-offs, online experiments are useful evaluation methods that can complement in-lab evaluations. It is particularly useful when researchers want to compare several visualization candidates through an experiment design (e.g., between-subjects study) with relatively low cost.

### 5.4.3 Evaluations in the Field

Through in-lab studies and online experiments, researchers can assess the effectiveness that glanceable visualizations provide, such as glanceability, perceived simplicity, and behavioral intention. However, these studies are not enough to capture other unique values of glanceable visualizations such as suitability, purposefulness, and short- as well as long-term effects on people's behaviors. It is also common for glanceable visualizations to support or accompany other tasks (e.g., catching a bus, driving a car), and therefore, the evaluations should ideally be situated for ecological validity. Moreover, glanceable visualizations are meant to be embedded in our everyday lives, and even worn on our body. Therefore, subjective metrics, such as calmness (in terms of interaction and timing; see Riekki et al. [46] for an overview of the framework), aesthetics [27, 43, 47], and expressiveness [27] may also be considered, along with more utilitarian metrics such as data insights gained over time and their effects on people, for example, behavior change. Because these metrics can be measured through a prolonged and situated experience, researchers have conducted evaluations in the wild to capture these unique values.

One of the seminal works in glanceable visualization in the Ubiquitous Computing domain is UbiFit Garden by Consolvo et al. [17, 19]. In this work, the authors displayed an abstract depiction of people's physical activity using the garden metaphor on their smartphone's background screen. The goal of this work was to encourage people's physical activity through enhancing their awareness of their current state. One of the design goals of UbiFit Garden was to communicate a person's physical activities and goal attainment using a non-literal, aesthetic image. The display was shown on the background screen as a subtle reminder whenever a person unlocks their smartphone. To evaluate UbiFit Garden, the authors first conducted a 3-week field trial, which was aimed to examine people's reactions to activity inference and the overall concept [17]. This study was followed by a 3-month deployment study, which was aimed to systematically examine the effectiveness of glanceable visualizations on people's awareness and actual behavior [19]. Such a stepwise evaluation approach is particularly useful in understanding a technology's impact on people's actual behaviors.

### 5.4.4 Summary

In this section, we described types of evaluation studies conducted to study specific characteristics of glanceable visualizations. Evaluations in the lab affords assessing minimal timespans needed to perform a task in ideal settings. In particular, this is useful when actual display conditions such as the size of the displayed data items or viewing angles need to be controlled. Online experiments reach a wider audience and collect data on questions that focus on accuracy or subjective experiences related to aesthetics or the simplicity of findings. Field studies in general yield higher ecological validity, and such methods are particularly useful in the case of longer-term behavior related research, or examining glanceable visualizations in the real context of use (e.g., interacting with visualizations while moving) in diverse environments (e.g., factoring in light and noise condition). While in this chapter we described evaluation methods for glanceable visualizations, many of the methods are suitable for evaluating mobile visualizations at large. Chapter 6 offers a general evaluation framework to cover more diverse mobile visualization contexts.

## 5.5 DISCUSSION AND FUTURE CHALLENGES

Different communities have been studying glanceable visualizations, and they have developed different perspectives of glanceable visualizations. Unifying these perspectives and goals from the different domains is impossible, however, showing the different time scales of glanceability can help researchers position their work. At the same time, such a unified overview can help to communicate the ideas of glanceable visualizations to practitioners and help to bring them to real-world applications and the people using them.

If we take the ideas of glanceable visualization one step further, we can imagine scenarios in which people are not only checking their devices for quick information needs, but they are surrounded by (augmented) glanceable visualizations, as for example, in Hyper Reality (`http://hyper-reality.co/`), requiring them not only to digest the information they are seeing at a glance but also to decide which information is currently relevant for their task at all, and in an extreme scenario ignoring the ads and suggestions continuously displayed. Now, more than ever, design guidelines for good and useful glanceable visualizations are needed.

One dimension we have not discussed in this chapter is the complexity and quantity of data to display. Creating glanceable visualizations of complex or a large amount of data is not always possible (or not even appropriate) as they may not be properly visualized with simple representations. It is also unclear how to embed glanceable visualizations in more elaborate application contexts. For instance, most glanceable visualizations we discussed so far require passive interactions (see Section 5.3.1). However, as not all data can be depicted so that it can be perceived at a glance, suitable interaction mechanisms become necessary for gaining further insights. Therefore, a next logical step is to explore ways to efficiently interact with (complex) mobile visualizations so that only quick glances are required to see where to interact and to perceive the feedback of an interaction. Further, with the advent of novel device classes such as head-mounted AR displays and related visions of the future such as situated, embedded, and immersive visualizations, there is a growing need for concepts on how glanceable content can be provided as well as be made interactive within such environments. For now, we refer the interested reader to Chapter 3 for more information on interaction on mobile devices and to Chapter 9 for a discussion on future visualization environments.

The types of evaluations discussed above have different ranges in the level of ecological validity. Although lab experiments give complete control to the study designer, they have little ecological validity, whereas online experiments give up some part of the control but have more ecological validity. Evaluations in the field are usually the experiments with least control but they have the most ecological validity. Therefore, a designer has to choose between the level of control and the level of ecological validity when conducting experiments. However, as one of the main usage contexts of glanceable visualizations is their use *on-the-go*, both lab experiments as well as evaluations in the field are necessary to fully evaluate a novel glanceable visualization.

## 5.6 CONCLUSION

In this chapter, we have discussed glanceable mobile visualizations and the quick information needs that fuel the design of such visualizations. We have looked at the time scales of glanceability in the Vision Sciences, the Visualization domain, and the Ubiquitous Computing community as well as the goals and tasks each domain investigates. In addition, we briefly touched on the history of glanceable (mobile) visualization, which stems from ambient and peripheral devices that research has studied since the 1990s and the current trend in developing visualizations that are often small in form factor and focused on for only a short period of time. Based on the perspectives, we have suggested core values for glanceability—presence and access, simplicity & understandability, and suitability & purpose. These core values form useful design considerations and can help to specify how glanceable visualizations might be studied for not only efficiency and accuracy, but also for evaluating aesthetics, and understanding potential behavior change. Even though research concerned with glanceable visualization has been around for over 30 years, with the onset of new mobile devices, new research questions have and are emerging, offering exciting research futures to explore.

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