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Visualizing Information on Smartwatch Faces: A Review and Design Space

Alaul Islam, Tingying He, Anastasia Bezerianos, Tanja Blascheck, Bongshin Lee, and Petra Isenberg

Abstract—We present a systematic review and design space for visualizations on smartwatches and the context in which these visualizations are displayed—smartwatch faces. A smartwatch face is the main smartwatch screen that wearers see when checking the time. Smartwatch faces are small data dashboards that present a variety of data to wearers in a compact form. Yet, the usage context and form factor of smartwatch faces pose unique design challenges for visualization. In this paper, we present an in-depth review and analysis of visualization designs for popular premium smartwatch faces based on their design styles, amount and types of data, as well as visualization styles and encodings they included. From our analysis we derive a design space to provide an overview of the important considerations for new data displays for smartwatch faces and other small displays. Our design space can also serve as inspiration for design choices and grounding of empirical work on smartwatch visualization design. We end with a research agenda that points to open opportunities in this nascent research direction. Supplementary material is available at: <https://osf.io/nwy2r/>.

Index Terms—Smartwatch visualization, Smartwatch face design, Design space, Mobile data visualization.



1 INTRODUCTION

SMARTWATCHES are powerful personal data collection devices and allow wearers to see various types of data measured from their body, their activities, or their environment. Previous research has shown that people can perform simple comparison tasks with visualizations on smartwatches within several hundred milliseconds [1], providing evidence that visualizations are effective forms of data representations in the context of wearable devices. The usage context and form factor of small wearable displays, however, pose unique design challenges that require further dedicated research. In this work, we focus on reviewing watch face designs, the context in which visualizations are shown, establishing a design space for smartwatch faces in terms of data and visualizations they can communicate, and pointing to open research opportunities for smartwatch visualizations.

Watch faces, the home screen of a watch, are the most frequently seen screen of a smartwatch. One of the difficulties of visualization design for smartwatch faces is the many types of independent data (e. g., steps, weather, battery levels) that often need to be embedded in a coherent watch face design. These non-time/date functionalities on smartwatches, that can be represented as visualizations, are called *complications* in horology [2]. Watch faces can be considered small personal dashboards with distinctive design challenges. The design challenges include a limited display space for possible complications, unique device form factors, the desire to express personality through watch face themes and design styles, and the mobile usage context that requires information to be readable at a glance. In addition, watch faces require that time or date is readable as the primary data.

We conducted a first systematic investigation into the different constraints and considerations for the design of data representations for smartwatch faces. Specifically, we build on our prior short paper [3], in which we report on a survey that asked smartwatch wearers to describe their current watch face and displayed data. Our prior work, however, did not systematically analyze how visualizations were integrated in a coherent watch face: we did not investigate how charts were drawn, if watch faces used specific themes that applied to visualizations, or to what extent smartwatch face designers used graphical decorations that could affect visualization style and reading. To address these limitations, in this work, we systematically analyzed 358 premium watch faces according to design dimensions, such as smartwatch components (e. g., time display, number of complications, graphical decorations) and visual features (e. g., interface styles, animations, color) as they could impact visualization style and reading. We compare our current review to our prior survey and derive a design space (see Fig. 1) for visualizations on smartwatch faces. This design space reflects design considerations related to external and device factors, watch face themes and styles, watch face components, and their visual representation. We end with a research agenda and summarize future work on watch face visualizations.

2 RELATED WORK

Most of past research on smartwatches has targeted smartwatches' technical capabilities (e. g., battery life [4], resolution [5], sensors [6], interaction techniques [7], [8], data collection methods [9], [10]), or their role in people's life [11]. Much less work has focused on how to represent information on a small screen or how to design visualizations in the context of watch faces. The work most closely related to visualization design for smartwatches focused on particular design contexts such as health [12], [13] or design ideations [14], [15], [16] for smartwatch data representations. In this section, we first review work that solely discusses smartwatch visualization challenges and then briefly summarize previous work on smartwatch representations on watch faces and in applications.

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Fig. 1: The dimensions of our smartwatch face design space that can influence visualization design and reading, with examples. Watch face images (a, b, and f) indicate personal fashion preference as a factor; watch face images (c, d, and f) show examples of watch face design styles; and other watch faces (c to h) regions highlighted in magenta color are—a logo (c), a container (d), a screen frame (e), a divider (f), a foreground graphic (g), and a background graphic (h). *Figure acknowledgements can be found before the references.*

2.1 Smartwatch Visualization Challenges

Tasks. Albers et al. [17] showed that tasks viewers conduct when exploring a visualization are influenced by the design of visual displays and choices of visual encodings, such as position and color. Additionally, the mapping variables employed in visualization, including the approach to data aggregation, also influence the viewers’ tasks. For instance, a visualization may show the raw data or averages. Computed aggregates enable the visualization to perform tasks that would otherwise fall to the viewer. Designing smartwatch faces to align with common tasks is important because designs may impact the wearers’ tasks. The properties of smartwatch faces may also affect visualization reading tasks (e. g., space available, complications/visualizations shown), may constrain visualization design (overall style or theme that needs to be followed), and may be competing for visual attention (e. g., decorations). Smartwatches also present distinctive usage challenges that are much unlike the usage of visualizations on desktop screens. For example, on average people look at a smartwatch for just 5–7 seconds [11], [18], [19], primarily to read the time (around 1.9 seconds [11]). The extent to which additional information can be understood from a quick look at the watch face remains uncertain. To answer this question, researchers studied low-level perceptual tasks to understand glanceability of smartwatch visualizations [1], [20], the impact of visual parameters (e. g., size, frequency, color) on reaction times [21], or representation preferences in an air traffic control usage scenario [22].

Representations. Recently, researchers started to conduct dedicated research on dedicated visualization techniques for smartwatches. Some of these research efforts target novel types of representations such as Chen’s temporal data [23], Suci and

Larsen’s time spiral [13], or Neshati et al.’s compressed line charts [24], [25]. In their exploratory studies, Amini et al. [12] showed that minimal designs and simple data-driven visualizations in the form of charts have great potential to support in-situ data exploration on small smartwatch displays. Pektaş et al. [26] showed how simple diabetes-related visualizations using icons and emojis on warnings and alerts could motivate wearers to monitor health-related information. Gouveia et al. [15] proposed six design qualities for smartwatches through an iterative ideation process. These design qualities include abstraction, integrating with activities, supporting comparisons to targets and norms, being actionable, leading to checking habits, and facilitating engagement when designing representations for glanceable feedback on physical activity trackers.

Customization and Personalization. Despite the growing capabilities of smartwatches, which can effectively capture and communicate a vast amount of information to wearers, some wearers risk abandoning these devices and missing out on potential benefits. This can occur when there is a lack of context-specific data representation or inadequate design of visualizations. Niess et al. [27] studied the impact of various approaches to represent unmet fitness goals on trackers through visualization on rumination, highlighting that multicolored charts on fitness trackers may lead to demotivation and negative thought cycles. Havlucu et al. [28] interviewed 20 professional tennis players and found that the abandonment of their fitness trackers was due to the type of information displayed on the smartwatches. The participants wanted specific tennis-related information, including recovery rate, nutrition, and details about their performance. They were interested in knowing where the ball hit their racket, the speed of a stroke, how

the ball bounced off the floor, overall mobility on the court, and any weaknesses or errors in the game. Schiewe et al. [29] studied real-time feedback during running activities for 40 participants. Their participants preferred visualizations over textual representations for self-serviced concurrent visual feedback on smartwatches.

Our work focuses primarily on visualizations on smartwatch faces. Being the home screen of a watch, watch faces are the most frequently seen screen of a smartwatch. It is important to understand more broadly how these small-screen displays are designed, as they provide the context in which visualizations may be seen.

2.2 Data Representations on Smartwatch Faces and in Smartwatch Applications

To review studies on data representations on smartwatch faces or in smartwatch applications, we collected publications that only discussed smartwatch data displays for applications, watch faces, or both. Of the papers we found, five [12], [14], [30], [31], [32] focused on broad design ideations either on watch faces or on both watch faces and watch applications. Three papers [1], [20], [33] investigated the perception of data reading and comparison tasks on smartwatch visualizations. The other papers focused on specific application contexts such as health [13], [26], [34], [35], enterprise applications [36], [37], [38], [39], driving [40], [41], sports activities [42], [43], [44], map navigation [45], [46], [47], child care [16], [48], smart-home [49], [50], air traffic control [22], and library management [51].

The works most closely related to ours concern smartwatch face designs. We found only two papers [15], [30] that focused entirely on smartwatch faces. Gouveia et al. [15] focused on glanceable physical activity feedback for smartwatches derived through an iterative ideation process. They recommend glanceable feedback on the smartwatch face to prompt further engagement with the presented information. Esakia and Kotut [30] describe five guidelines for designing smartwatch applications and evaluated them in a mobile computing class, in which undergraduate students considered the applications as part of a design and development cycle. The design guidelines helped students develop watch faces in the context of a project promoting community physical activity.

With a similar focus on application areas, some research discussed representing health and physical activity data on smartwatch faces [13], [25], [26], [34], [52]. Recommendations for watch face designs from these papers were sparse. Neshati et al. [25], for example, recommended a space-filling line chart technique and associated interaction techniques for time-series data. Van Rossum [52] recommended aiming for understandable and clear visuals, especially for people with deteriorating eyesight, using a black background for contrast in dark environments.

Others reported watch face design ideas from ideation activities, workshops, or design space explorations on smartwatch data representations [14], [31]. Carpendale et al. [14] offer new context-specific smartwatch applications and watch face design ideas from a range of situated ideation exercises. Klamka et al. [31] show eight wearable application ideas and prototypes for personal information and mobile data visualizations with bendable color ePaper displays. In contrast, we focus on general smartwatch faces with a broad, everyday, usage context in mind.

In our previous short paper [3], we studied which data people currently consume on their watch faces and how it is visualized. Our goal was to collect data that would allow to ground future studies on smartwatch visualizations (e. g., to inform choices about how many

TABLE 1: Redrawn example representations from real smartwatch faces published in our short paper [3]. Text colors correspond to three data categories: **Health & Fitness**, **Weather & Planetary**, and **Device & Location**. Bluetooth and wifi *Only Text* and *Only Icon* change color based on on/off status.

Data Types	Only Text	Only Icon	Icon+Text	Only Chart	Text+Chart
Heart rate / ECG waveform	68 bpm		68		
Step count	3168 steps		3168		
Sleep related info	1h 13m REM 4h 11m light		6:53m		
Distance traveled	1.19 Miles DISTANCE		1 Mile		
Calories burned	64 Cal		1,603		
Floors/Stairs climbed	31 floors		13		
Blood pressure	SYS DIA 120 / 81		126/78		
Weather info	PARTLY CLOUDY				
Wind speed/direction	Wind ESE at 3mph		West		
Temperature	37°C		14C		
Sunset/Sunrise	6:34 PM SUNSET 7:14 AM SUNRISE		7:14 am 6:34 pm		
Moon phase	Moon Age: 25.43 Days		25.45 17% Moon		
Humidity	40% HUMIDITY		42%		
Bluetooth	BLUETOOTH				
Phone battery level	Mob 85%		100%		
Location name	Paris		Normandy		
Wifi	wi-fi		3 bars		
Watch battery level	WATCH 44%		88%		

visualizations to test) in current practices of smartwatch wearers. Our prior work made the following contributions: we conducted an online survey with 237 smartwatch wearers, we conducted an online search of smartwatch face visualizations reprinted in Table 1, and we analyzed the potential for future smartwatch visualizations, in particular what data could be visualized by looking at the technical capabilities of the watches our participants wore.

Although this first survey yielded many interesting findings, the study had several limitations that we address in this article. Specifically, we did not collect (i) the types of visualization charts used on smartwatches; and (ii) how representations were integrated within other watch face visuals (such as themes). This work complements our prior survey by systematically reviewing commercially available smartwatch faces and structuring a visualization design space for smartwatch data.

3 A SYSTEMATIC SMARTWATCH FACE REVIEW

To complement our prior survey [3] and to gain a deeper understanding of design considerations for smartwatch faces, we collected watch face designs and conducted a systematic review. We study smartwatch faces because they are the context in which smartwatch visualizations are shown, and thus they may influence

visualization design (e. g., if an overall style or theme needs to be followed) and visualization reading (e. g., available space, number of complications). Studying smartwatch faces, in particular data shown on them, also highlights opportunities for visualizations. In this section, we detail our methodology and report results.

3.1 Data Collection and Analysis

Our prior work [3] relied on participants’ own descriptions of their smartwatch faces that we could not systematically verify. To address this limitation, we conducted a systematic review of premium (paid) watch faces from a popular watch face app and website. We focused on premium watch faces because we considered these to exhibit an acceptable level of design professionalism. The alternative of collecting watch face screenshots from a large number of participants would have been technically infeasible and potentially privacy invasive. Screenshots are difficult to take and transfer from watch to study platform for non-tech-savvy populations and watch faces often contain privacy sensitive information, such as locations or body measurements.

We, therefore, decided to collect watch faces from the Facer App [53], one of the most popular smartwatch face distribution websites. It contains a Top100 page that lists the premium or free watch faces of Apple and watches running the WearOS/Tizen operating system. (Because WearOS and Tizen are closely related, we refer to both as WearOS from now on.) According to a Facer forum, the number of weekly syncs or downloads made decides the Top100 list. The list resets every Sunday at midnight (00:00). To become a premium designer on Facer, one must have three designs that received 3000 syncs in 30 days.

We manually collected the metadata of the top 100 premium smartwatch faces every Sunday at midnight for one month, starting from March 14, 2021, for WearOS smartwatches and starting from September 18, 2022, for Apple smartwatches. When we began this work, the Apple list did not consistently contain 100 watch faces; therefore, we had to collect this data later. The metadata collected for each watch face included its rank, name, link, and thumbnail.

Among the 800 top watch faces we collected, 358 were unique watch faces as several appeared in the top 100 for multiple weeks in a row. Some watch faces in the list were also extremely similar, and if so, we chose only the first instance collected during the initial week. To be considered unique, we looked at each watch face’s distinctive characteristics: the data types shown, representation forms, UI style, time display, and graphical decorations (such as logos, backgrounds, or screen borders). For example, some watch faces differed only in a single complication or by color palette from the same watch face designer. We eventually selected 358 watch face designs from the initially collected 800 top watch faces.

To compare and analyze these 358 unique designs, we derived a set of codes that targeted an understanding of the overall design and how data representations were integrated in the watch face. We reviewed watch faces in the representative configuration shown on the Facer website (i.e., the configuration the watch face designer chose). Wearers can usually configure watch faces once installed, but we could not capture custom configurations. We acknowledge this as a limitation of our approach. Table 2 lists the codes we used. On a higher level, we focused the codes on *what* is being represented and *how* it is shown. We provide these codes as a supplementary file.

We conducted all analyses using the extracted image of each watch face. In case a design was not clear from the thumbnail,

TABLE 2: Codes used in the review of smartwatch faces.

	Dimensions	Values
Smartwatch Components	time display	digital, analog, hybrid
	complication count	0, 1, 2, ...
	complication type	watch battery, steps, calories, ...
	graphical decoration	container, logo, background/foreground graphic, screen frame, divider
Visual Features	number of hues	0, 1, 2, ...
	UI style	skeuomorphism, semi-flat, flat
	animation	animation for graphical decoration, data-related animation (heart rate, watch battery, weather, etc.)
Representation type		text, icon, chart, or combinations

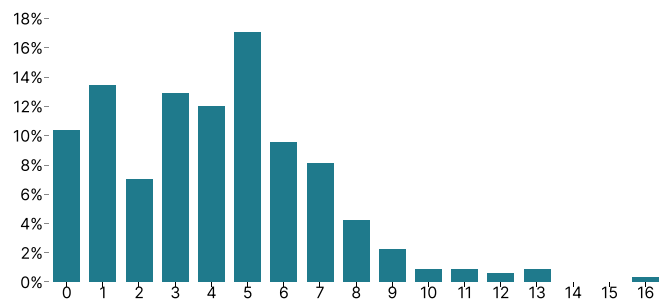


Fig. 2: The percentage of watch faces (y-axis) corresponding to different numbers of complications (x-axis).

we went to the Facer website to look at the simulated watch face graphic. We grouped our results according to the components shown on a watch face and how they were shown. We compared the results relating to the number and type of complications, time display, and complication representation between the current review and prior survey. We analyzed the results regarding graphical decorators, hues, animation, and UI style in the current review.

3.2 Results

3.2.1 What is Displayed on a Watch Face?

Number of Complications. The watch faces contained a median of 4 complications similar to our prior work [3], in which participants reported a median of 5. However, we saw a difference in the number of watch faces with only one complication. While (13.41% \blacksquare) (see Fig. 2) of the premium watch faces contained only one complication, in our prior work [3] only (0.84% \square) of the watch faces contained one data item. The maximum number of complications per watch face drawn was similar: 16 in this review and 17 in the prior work [3].

Types of Complications. Health-fitness data was the most common, followed by weather & planetary and device-location data echoing the results of our prior work [3]. Watch battery level ranked first again as well. The main different to our prior work related to Bluetooth connectivity data which was ranked 8th previously [3] but did not appear in the current review of data types, perhaps because Bluetooth icons only appear when a watch is paired to a phone and, therefore, did not show in our thumbnails.

3.2.2 How is the Watch Face Designed?

Watch faces consist of components representing time, complications, and decorations, each with their own representation styles.

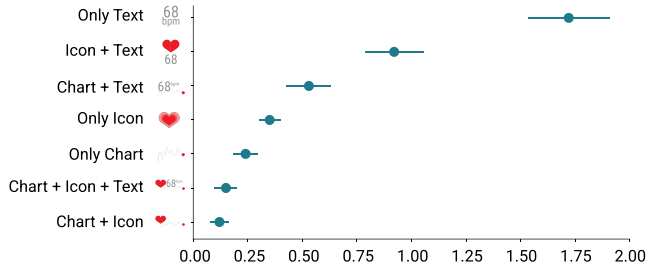









Fig. 3: The average number (x -axis) of representation types (y -axis) presented on the premium watch faces.

Time display. We categorize watch faces based on the type of time display they employ, as different time displays may interfere with other visual components differently (e. g., analog hands may overlap visualizations and digital time displays may take up a considerable amount of space). Time displays can be divided into three categories: digital, analog, and hybrid, allowing us to categorize watch faces accordingly. Digital watch faces represent time information as HH:MM:SS for hours, minutes, and potentially seconds. Analog watch faces typically use the hour, minute, and second hands to indicate the time, to resemble conventional analog watches. Hybrid watch faces have both digital and analog time displays. We found that the majority of premium watch faces were digital watch faces (60.3% ) , followed by analog watch faces (26.3% ) and last hybrid watch faces (13.4% ) . The ranking of time displays was the same as in our prior work [3] with small variations in the percentages (64.6% digital, 23.2% analog, 12.2% hybrid).

Complications Representations. We found seven ways complications were represented based on combinations of text, icons, and charts. As icons, we classified graphical content not in the strict semiotic sense and more analogously to how they are used in computing. Here, icons are a type of image that represents something else. As such, our icons can be both semiotic symbols  and icons  . Fig. 3 shows the representation types on average displayed on watch faces found in our review. The most common representation forms observed were text, icons, charts, and their combinations.

A simple text label (Text Only 68_{bpm}) was the most common representation type for 1–2 data types on average on each watch face ($M = 1.72$, 95% CI: [1.53, 1.91]). Icons accompanied by text labels (Icon+Text 68_{bpm}) were the second most common ($M = 0.92$, 95% CI: [0.79, 1.07]). In our prior work [3], Icon+Text had been the most common representation type, used to display two kinds of data types on average on each watch face ($M = 2.05$, 95% CI: [1.78, 2.32]) followed by Text Only ($M = 1.38$, 95% CI: [1.13, 1.66]). Both results show that text seems to be the most frequent way to represent data on watch faces while charts or charts combined with text or icons are rare in practice. One notable difference in the data was the difference in Only Icon displays. Examples for representations that rely purely on a small image, such as weather icons ( ) are still rare on watch faces (see Table 1). Yet, in our prior work [3], surprisingly a large number of participants reported seeing Only Icon displays ($M = 1.11$, 95% CI: [0.93, 1.3]), which we attribute to a potential misunderstanding of the category. In our current review, Only Icon displays were, as expected, much more rare. We saw them for weather data (99 \times), moon phases (23 \times), wind directions (3 \times), compass/direction finder (1 \times), and altitude (1 \times).

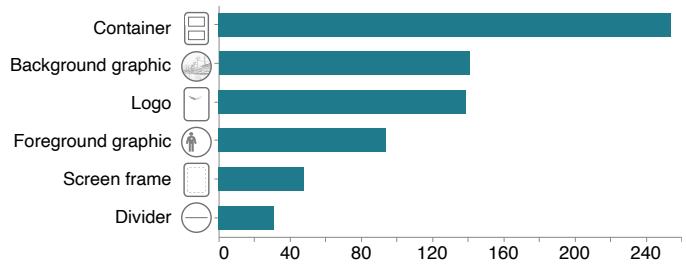


Fig. 4: Number of watch faces (x -axis) containing graphical decorators (y -axis) found in the current review.

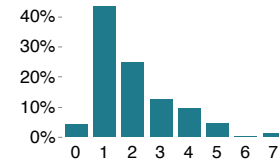








Fig. 5: Percentage of watch faces (x -axis) with a certain number of hues (x -axis) in the current review.




For the following watch face components, we only report results from the current review because we had not asked participants about them in the prior work [3].

Graphical Decorators. We define graphical decorators as graphical content on the watch face that forms a coherent unit and takes up space, similar to complications, but does not carry any data. We found six types of graphical decorators (see Fig. 4). *containers* (254 \times), which surround other watch face components; *background graphics* (141 \times), which are decorations on the background such as a wallpaper; *logos* (139 \times), which are small images to represent the brand or designer of the watch face; *foreground graphics* (94 \times), which are other decorations in the foreground, such as small images or lines; *screen frames* (48 \times), which are decorations on the border such as frames; and *dividers* (31 \times), which are the lines that split the watch face into dedicated regions.

Number of Hues. To get a better sense of the overall look of the watch faces, we analyzed the main hues used. We did not consider black, white, and gray because these dominate most backgrounds. Nearly half of the premium watch faces (43.30% ) had only one hue (see Fig. 5). More than a quarter (24.58% ) had two, and only one-eighth (12.57% ) had three hues. The maximum number of hues on one watch face was seven.

Animation. We found that 80% () of the top watch faces had no animated content; 20%  had animated content that did not represent data. Animations were used either on decorations or on complications to make them look more vivid and stand out. Sometimes animations were meant to make content even more iconic, such as a heartbeat animation for a heart icon  .

UI Style. Through the user interface (UI) style code, we captured the overall appearance of the watch faces. We found three categories of styles: skeuomorphism, flat designs, and semi-flat designs as shown in Fig. 1 (Style/Theme). In UI design, skeuomorphism is used to describe a graphical interface style, in which elements mimic their real-world counterparts [54]. Skeuomorphism deploys gradients, shadows, or ornate details [55] and on watch faces, these design elements are often used to recreate elaborate analog watch faces, such as those of pilot or diving watches. Flat design is a graphical interface style, in which no graphical elements attempt to create the appearances of continuous 3D depth. This style highlights

simplicity by concentrating on two-dimensional elements, clean lines, and bright colors [55]. Semi-flat designs are in-between flat design and skeuomorphism: they are flat designs with some realistic touch, such as shadows. We found flat (36.87% ) to be the most popular style, followed by skeuomorphism (33.80% ) and semi-flat (29.33% ) designs. The flat design was more frequent on Apple (56.32%) than on WearOS watch faces (18.48%), while Skeuomorphism was more frequent on WearOS (54.35%) than on Apple watch faces (12.07%).

Factors Influencing Design Popularity. Our metadata contained watch face ranks ranging from one to a hundred. We analyzed unique watch faces categorized by their ranks as coded in the metadata, aiming to uncover patterns and reasons behind the varying popularity of different designs. Watch faces ranked 1 to 50 exhibited an average of at least four complications, while there was a decline in complications beyond rank 50. Wearers seem to prefer watch face designs with a minimum of four types of complications, as supported by our prior work [3]. We also explored representation types and found that trends in data representations were similar between top-ranked (1–50) and lower-ranked (51–100) watch faces. Minimal color usage was preferred in watch face designs, as evidenced by fewer hues in the top-ranked faces compared to those beyond rank 50. Additionally, we examined graphical decorators and found that in the top-ranked watch faces (1–50) graphical decorators were consistently more prevalent. These findings indicate that the number of complications, color usage, and graphical elements may play a role in shaping the preference for watch face designs among wearers. Future studies on design preferences will help gain deeper insights into what constitutes an appealing watch face design or a good design practice. A historical analysis in a few years might also reveal interesting results regarding preference changes and potential fashion trends.

4 DESIGN SPACE

Our review of existing watch face designs gave us the opportunity to reflect deeply on the design of watch faces. In this section, we generalize our findings into a broader design space. Our goal is to systematically structure considerations for a holistic watch face, to shed light on the integration of visualizations.

Inspired by our previous evaluations, the design space is primarily descriptive [56]. It allows to describe existing watch faces based on a variety of factors. The design space also has the potential to be generative in that its individual components could inspire new watch face ideas. However, we have not yet verified the design space as such. Fig. 1 gives an overview of our design space with examples. The figure shows four main dimensions that are important to consider in the design of a watch face. The design space is based on our initial codes for the watch face designs listed in Table 2. Data collection and analysis of actual watch face properties led to the design space dimensions after several rounds of discussion among the co-author team. The *Style/Theme* dimension aligns with the *Visual Features* from Table 2. To make the design space comprehensive, we included *Font Style* and *Texture* in this dimension, because our review and existing literature [57] indicated their significant impact on the overall styling and theme of visualization designs. The dimension *Components* is derived from the *Smartwatch Components*, introducing *Input Widgets*, which include interactive buttons/icons commonly found on watch faces but do not convey categorical or numerical data. The *Representations* dimension

emerged from the initial coding *Representation Type*, encompassing *Data Types* and *Visual Features* influencing watch face visualization. We added an additional dimension in Fig. 1 called *Externals*, which considers the smartwatch device itself and individual usage context, impacting the overall design. While not part of the watch face designers’ coding or listed in Table 2 these device and personal factors certainly may be important in the design of watch faces.

Unlike some other design spaces, our dimensions are not independent. They are ordered in a sequence (left to right) to show the dimensions’ main direction of influence. We consider watch faces to be multi-view displays or data dashboards in which the designer carefully chooses what to include and how to style & arrange them. For developers taking inspiration from our design space, we recommend to complement their reading with a look into the specific developer guidelines for watch faces on the final platforms (Android [58], Apple [59], etc.). These guides typically have additional broad guidance and feature descriptions available on each platform (such as automatic layouts, types of complications supported, etc.). Here, we cover platform-independent features needed to create holistic watch faces.

4.1 Watch Face External Factors

Factors external to the watch face may influence its design (Fig. 1 Externals). The watch itself (device driven) defines the shape (form factor), display size (watch dimension), display type, and display resolution, which may influence choices in other parts of the design space. For example, the display type (such as OLED or E-ink) has a great influence on colors available to style the graphics and to represent data as visualizations.

E-ink watch faces, for example, have fewer colors and lower display refresh rates making animations difficult. They nevertheless have the potential for sport and activity smartwatches because of their paper-like characteristics, lightweight nature, low battery consumption, and readability in sunlight [60]. In contrast, OLED displays have greater color quality than other technologies. In recent years, OLED displays have risen to prominence as the main display technology for wearable devices. Most high-end smartwatches, including Apple and Samsung, use this technology. Due to the excellent image quality, OLED displays offer great possibilities for fashionable smartwatch face designs.

In addition to the display type, the display shape (form factor) has a profound impact on the layout and the graphics design. Watch faces now mostly come with square or circular displays; content is often shaped to match and create a harmonious aesthetic, which can, in turn, constrain the types of visualizations that can be shown. Moreover, personal factors such as intended usage context or fashion preferences play an important role in the watch face design. Purchasing decisions may be made on whether a smartwatch would be wearable in casual or business contexts and whether it goes with a certain fashion, as seen in previous work [61]. We expect that for some wearers similar decisions play a role for smartwatch faces and their design styles and overall look and consequently visualization use.

4.2 Styles, Themes, and Topics

The theme of a watch face design describes a set of design attributes applied to all elements of the watch face to create a consistent, unified, or coherent look (Fig. 1 Style/Theme). These attributes may define a set of colors used or visual textures imitated, the overall UI style, and potential animations used. Themes can also influence

other dimensions such as the components of the watch and their representation. For example, a watch face with a minimalist theme may show only a few essential components such as a digital time, date, or battery life represented with simple visual features.

A theme may relate to a topic such as fitness, outdoor sports, games, and fashion. For example, Fig. 1 (d) shows a dedicated comic theme with a flat UI style, a set of primary colors, and comic-style fonts chosen, while Fig. 1 (f) depicts a semi-flat UI style going for an appearance of vintage-style weather components.

Watch face styles relate to themes and specify how specific components on the watch face are rendered. For example, in Fig. 1 (d), the fonts for labels use a comic style that matches the comic theme of the watch. Specific color-related design themes and styles are common on watch faces. For example, a darker color palette for the background is used most of the time perhaps to enhance content readability without disturbing wearers with bright light during the night or to save battery [52]. The flat and skeuomorphism UI style is extremely popular, whereas semi-flat designs are used frequently when the watch face is meant to be different and unique compared to traditional watches. Themes including animation often aim for a vivid overall feel but rarely use animation to represent data.

Both themes and styles influence how data representations on a watch face can be designed. Aiming for a consistent design would affect graphical embellishments or decorations such as shading used in visualization but also the available colors and potentially the types of visual channels that can be used. A watch face with a black-and-white theme, for example, cannot use multiple categorical color encodings based on hues.

4.3 Watch Face Components

We define components as any coherent object on the watch face that takes up display space, including complications, time-date-related data, graphical decorators, and input widgets (e.g., functional buttons) (Fig. 1 Components). Designers have to decide which type of components to display and how many of them to put on the watch face. Only two types of components display data: time-related components (time, date, or day) and non-time-related components, called complications [58] in horology. Graphical decorators refer to elements on smartwatch faces unrelated to data, for example, logos, screen frames, or background images. Input buttons such as settings or audio buttons are typically represented by icons on a touch-enabled smartwatch face and do not reflect any categorical or numerical data. Designers should avoid unfamiliar metaphors while designing or choosing such icons so that wearers can quickly understand their functions. The choice of type and number of watch face components is closely related to the theme of the watch. For example, an aviation-themed watch (Fig. 1 (c)) may require specific time-related components to show the time zone, a chronograph, and a date display, and it is likely to use a skeuomorphism design style. A fitness-themed watch face (Fig. 1 (b)) might instead require a large number of complications for showing step count, heart rate, or calories burned.


The choice of an analog, digital, or hybrid display of time on the watch face also has an impact on the overall design. Analog watch faces have dials that may overlap complications and make them less readable. Digital watches use fonts that need to fit the general style and typically take up a prominent position on the watch face leaving less space for other complications.



Graphical decorators also play an important role in smartwatch faces. Through them, themes can often be expressed, and they, too,

can constrain the space available for complications. Containers are a particularly frequent graphical decorator that partitions the watch face into regions and gives dedicated display space to complications. For example, Fig. 1 (d) uses a lot of space for comic-related background images and comic panel containers and constrains the complications to fit into speech bubbles. Decisions on which and how many components to display have an impact on how the components can be represented as discussed in the next section.

4.4 Watch Face Data Representations

Each watch face component's digital representation has at minimum a position, size, shape, and color scheme or texture (visual features). In this section, we focus our discussion on watch face complications that represent data other than time (Fig. 1 Representation).

One of the difficulties of designing a complication for smartwatches is that the data category it shows needs to be identifiable, for example, as steps, heart rate, or calories. Designers can place signs to identify data categories or rely on wearers to learn and memorize a mapping. The types of signs that can identify a data category include—text labels that specify the category (e.g., “steps”), accompanying icons (e.g., a foot icon for step count), and text units (e.g., “km” for distance traveled). The “three rings” on the Apple Watch is instead, an example of a mapping that requires learning . It uses three concentric radial bar charts with memorable colors but without a sign to represent what each colored rings stands for: movement, exercise, and standing. One of the advantages of memorized mappings is that no display space needs to be dedicated to labels, units, or icons.

In our evaluations, we observed that most smartwatches face complications represented data with combinations of text, icons, and charts. Most data encoded a single data value . More complex encodings, however, are certainly possible (e.g., multiple points over time or space ) and designers can take inspiration from more complex micro visualizations such as in work on word-scale visualizations [62], [63] or data glyphs [64].

4.4.1 Representations by Data Type

We divided complications according to which data type they represent to discuss them in more detail: absolute numeric data, proportional data, categorical data, ordered data, temporal data, and geospatial data. Discussing complications by data type seemed more useful than by data category (e.g., steps, battery, . . .) as data in each category can easily be converted into different data types. For example, a step count can be an absolute numerical value (e.g., 6700 steps), converted to a proportion (e.g., 67% of a daily step goal), or shown as a time series. Next, we discuss representation possibilities and challenges based on the most common data types we saw represented on watch faces.

Absolute numeric data on watch faces commonly appears as either a single number or a pair of numbers. For example, the temperature can be a single numeric value (35°C) or pair of numeric values (Highest: 35°C; Lowest: 30°C). Absolute numeric data is theoretically infinite or has a large range. This data can be represented as text or in a chart but their visual representation poses major challenges when the values dynamically update. There is often not enough space for visual references such as labels, tick marks, or grids in smartwatch complications. Without these references, one would have to predict data mappings that fit in the given display space and ensure the display adjusts to the dynamic updates without confusing wearers. However, absolute

numeric data often has a limitation in practice that can help to predict value ranges. For example, step counts can be unlimited. In reality, considering the time limit (e. g., within a day) and/or the limitation of human physical abilities, the value corresponding to the step count on the smartwatch face has a potential limit. It can help to consider plausible limits for reserving display space, calculating color scales, and identifying whether meaningful differences in values (e. g., 100 steps) should remain visible in a chart. So far, perhaps due to these challenges, charts that visualize absolute numeric data on smartwatch faces are still rare. Only Text representations are the more common representation form.

Proportion data represents values according to a given maximum, typically 100%. Visualizations of proportions are common on watch faces: in Table 1, most of the charts in the last two columns show a proportion. We found data in the form of real proportions and derived proportions. For real proportions, the shown value corresponding to this data category has originally been captured or measured as a proportion, such as 42% humidity or 80% power (of a fully charged battery). Derived proportions are proportions converted from absolute numeric data to a proportion according to a pre-set maximum and minimum. One of the common derived proportions is from a goal watch wearers set, such as steps—67% (of 10k steps), calories burned—67% (of 3 kCal).

Categorical data is a type of data that does not have an implicit ordering. Categories only distinguish whether two things are the same or different [65]. Categorical data is often represented by small graphical elements. Common are icons that stand for the categorical value (weather—rainy ☁️/sunny ☀️) or a sign with an indexical color (Bluetooth—on 🔵/off ⚪).

As opposed to categorical data, **ordered data** does have an implicit ordering [65] (e. g., a low/middle/high level of the smartwatch battery). Most ordered data on watch faces is quantitative or has been derived from quantitative data. Icons or charts commonly represent ordered data with an ordered color scale encoding. Often, derived ordered data is encoded together with proportions. For example, battery indicators often turn red when the battery is almost depleted and green when it is fully charged.

Temporal data on smartwatch faces most commonly relates to specific time points such as sunrise or sunset time, time when one went to sleep or woke up, etc. Time series on a continuous scale are common for sleep data or heart rate. Designers often visualize some temporal data in conjunction with the dial of analog watch faces, such as sunrise and sunset times (Fig. 6 shows an example of sunrise time) that are displayed as icons next to the hour numbers. Nevertheless, the variety of temporal visualizations on watch faces is still small compared to the many visualizations for time that exist [66]. Especially designs for events and intervals are still rare on watch faces and how to port past ideas to a watch should be further explored (e. g., [67]).

The most common **geospatial data** on smartwatch faces concerns the wearer’s location and time zone. In addition to text and icons (e. g., landmarks 🏰) maps 🌐 also sometimes represent this data.

4.4.2 Representation Types

Text is the most common form of data representation on smartwatch faces. Text can be styled through font type, size, and color, which can also be used to encode additional information, for example, as

in word clouds. However, we rarely saw font-size based encodings on actual watch faces despite them having been mentioned in research [12].

Icons on watch faces are widely used for labeling but rarely to represent data. They can be used for categories if icons exist to meaningfully identify the categories. This is the case for weather data where viewers are familiar with icons that represent a rainy ☁️ or sunny ☀️ day. It would be harder to find icons that represent REM, Light, or Deep sleep stages.

There are two options to use an icon to represent quantitative data: a) designers can turn the quantity into an order or category and use a visual variable for categories such as hue, texture, or position or b) add a visual variable to the icon that can represent a quantity such as position, size, area, flicker, etc. For example, suppose a designer wants to represent the quantity of calories burned with an icon. In that case, they first have to choose an icon that represents calories; a fire icon 🔥 is relatively common. Next, the designer could apply a sequential color scale (🔴🔵🟢), size the icon relative to a quantity (🔥🔥🔥), or apply animation-related variables such as flicker. Icons can also be stacked to create unit-based pictographs. Similar examples we saw include step counts represented by different shoe icons (e. g., walking, running, climbing), but examples were rare.

Charts for data representation on watch faces were rare in our prior work and this review. However, charts have the potential to communicate information at a glance [1], but need to be carefully designed to account for the small display size [68], [69].

The *chart types* that were commonly used to represent data on the premium smartwatch faces were bar charts, pie charts, donut charts, gauge charts, area charts, pictographs, and sliding scales. The data type suggests the most effective chart type to use as discussed above. The chart type directly affects its possible shape, size, and, ultimately also its location. For example, several types of charts can be curved and then aligned with the rim of a watch face.

The *chart size* is related to the area occupied on the watch face. Size is more closely related to the shape of a chart rather than just its bounding box due to the tight layout of components on the watch. For bar charts and sliding scales, the size mainly refers to length and thickness. For pie, donut, and gauge charts, the size mainly refers to the diameter. For area charts and pictographs, the size mainly refers to their length and width. If a chart’s shape matches a watch screen’s shape, the chart can fill the watch face. For example, a donut chart can use the circumference of a round watch face. We rarely saw space-filling charts (similar to Dragicevic and Huot’s SpiraClock [67]). Often charts were nested inside round containers similar to complications on physical pilot or diving watch faces.

Chart color describes how many hues are used on the chart, to style the chart or to represent data. Black and white watch face designs exist, in which hue cannot be used to represent data. In this case, textures may be used to represent categories [70], but these are difficult to design well in practice. Decorators such as gradients affect a charts’ color and have to be used with care. Gradients consist of different saturation or brightness of the same hue or gradients of different hues. One difficulty of using hues for categorical color encoding on watch faces is that the hues need to match the overall theme and aesthetic of the watch face. A color scheme that might create an aesthetic design overall might not work well for encoding data and vice versa.

Chart position refers to the place of the chart on the watch face. Often charts are positioned somewhere in the middle of the watch face or in the periphery. The shape of the chart affects the possible



Fig. 6: A watch face showing sunrise time.

position of the chart. For round watches, ring-shaped or arc-shaped charts are most suitable for being located on the periphery of the watch face, whereas other shapes like bar- and line-charts can only be located in the middle of the watch face.

Chart theme refers to the theme of complications, which often conforms to the overall topic of the watch face. Charts used in research rarely have a theme but for watch faces, these should be explored further. Colors, shapes, and in particular textures can help to define a theme.

4.5 Summary

In summary, we present a design space for creating holistic watch faces considering four dimensions—externals such as personal and device factors, styles/themes, components, and representations—and their interplay in influencing smartwatch face design decisions. We further explore the various ways data can be represented on a watch face, including absolute numeric data, proportional data, categorical data, ordered data, temporal data, and geospatial data. Lastly, we delve into data representations on watch faces, such as text, icons, and charts, and discuss the challenges and possibilities of visualizing data on the limited display space of a smartwatch. In the next section, we discuss watch faces as small data dashboards and how our design space relates to dashboard design spaces.

5 DISCUSSION

The goal of our design space is to describe existing watch faces and the factors that may influence visualization placement, design and reading. These descriptions can be used to help compare different designs, to identify factors for assessing watch faces, and potentially help researchers generate new designs or variations of one design. In Fig. 7, we show four descriptions of popular watch faces that have been generated with the dimensions of our design space. In this section, we discuss factors related to watch faces that go beyond our design space and shed more light on external factors and interactivity. We then deliberate on important and promising research directions in the next section.

We consider watch faces as small data dashboards. Few [71] defines dashboards as “a predominantly visual information display that people use to rapidly monitor current conditions that require a timely response to fulfill a specific role.” Watch faces fit this definition well because they are visual displays that people glance at briefly to fulfill a specific information need. In their study on data dashboards Sarikaya et al. [72] survey the purpose, audience, visual features, and data semantics. Likewise, Bach et al. [73] propose eight groups of design patterns that provide common solutions in dashboard design. Here, we make use of their dashboard design space and discuss how it relates to ours.

Purpose. Sarikaya et al. [72] describe two purposes for dashboards: decision support (strategic, tactical, operational) as well as communication and learning. Bach et al. [73] consider dashboards communication tools that focus on decision-making needs of: information overview, control, and conciseness. Our design space covers watch face purposes under external factors that influence the watch face design, its themes, components, and representation of complications. Of the two purposes Sarikaya et al. mention [72], watch faces also concern decision support (“do I need to walk more?”, “should I leave for a meeting now?”) and communication in the wider sense by showing progress toward potential fitness

goals, the weather, or simply showing the time. However, watch faces have other purposes that were not covered in this past work, for example, entertainment (some watch faces contain games with other complications) or simply making fashion statements. Further research is needed to elicit these purposes: how people choose watch faces, and how the purpose may guide design decisions in other parts of our design space.

Audience. According to Bach et al. [73], novice dashboard users will need more instruction in the form of a clear layout and less information (e.g., single value, aggregated data), whereas expert or regular users will be more data literate and require more data and custom features on dashboards. Similarly, Sarikaya et al. [72] argue that the visuals and functions of a dashboard “reflect the intended audience, their domain and visualization experience, and their agency relationship with the data.” Watch faces are “individual” dashboards in Sarikaya et al.’s design space because they reside on a personal wearable device and are typically not shared with others. A broad range of the population buys smartwatches and there are now smartwatches targeted for children [74]. Designers of watch face visualizations, thus, cannot assume visualization literacy but many smartwatch wearers exhibit intricate familiarity with the data itself, their typical step counts, weather, or sleep patterns, for example. Most watch faces currently seem to be designed for people with low visualization literacy in that they mostly represent data through text and use simple graphs. Past work on word-scale visualizations [62], [63], however, has shown that complex representations are possible in a very small display space.

Interactivity and Visual Features. Interaction on watch faces has so far been quite restricted compared to what was found for more general dashboards [72], [73]. Interactions that we found relatively common were opportunities to tap through different types of data (e.g., switching from step counts to calories burned within one complication’s container). We also found some interactive games that could be played by touching a watch face. Sometimes interactive changes to watch faces were enabled through companion apps, in which the layout and type of data shown on a watch face could be specified. What we have not seen is watch faces that allow to input data, correct data, or highlight specific complications. In terms of visual design, Bach et al. [73] emphasized color consistency in overall dashboard design and advocated for reducing color, if not required, particularly for screen fit dashboard designs.

Additional Data Semantics. Several of Sarikaya et al.’s and Bach et al.’s additional data semantics apply to our work. In particular, “benchmarks” (e.g., step counts that have been reached) are commonly represented either by colors or by specific chart types, such as gauges and other proportion representations. Another similarity to their dashboards is regular data updates on watch faces and highlights when certain thresholds have been reached (e.g., critical battery levels or heart rates). These updates pose visualization challenges as outlined previously, especially for watch faces that are not monitored continuously.

6 RESEARCH AGENDA

While we have hinted at possible future research directions previously, here we highlight what we consider the most important or promising research directions for watch face visualization.

6.1 Holistic Study of Smartwatch Faces

Watch face visualizations do not only need to be small but they also need to be integrated into a coherent watch face theme. As

a personal data dashboard, watch faces not only make fashion statements but can also play an important role to facilitate decision making. We identified several open research questions that relate to the integration of visualizations in watch faces.

Designer’s Vision vs. Use in Practice. Through our prior work [3] and current review, we observed a tension between a watch face design vision and the use of watch faces in practice. While a big part of the market designs included a single complication (18%), 99% of people in our prior work [3] reported to have more than one complication on their watch face. We suspect that wearers often customize or personalize their watch faces to include more complications than the designer intended. Thus, while smartwatch designers may decide to follow design guidelines and recommended practices from the visualization community in their implementations, it is possible that smartwatch wearers make customization choices that violate these guidelines and practices. We can try to help wearers use a more appropriate design, for example, by suggesting best locations for placing a complication depending on clutter, background color, etc. Nevertheless, smartwatches remain personal devices, and wearers are (and should) ultimately be in control. As a community, we need to consider the right balance of allowing wearers to feel empowered in their customization, without being constrictive in our attempt to guide them.

Study of the Influence of Themes. The use of embellishments around data visualizations has been heavily debated in the visualization community. Some argue that they should be avoided [75]; some argue that they do not hurt or can even help [76]. Watch face visualizations have, by design, a number of visual distractors surrounding them. UI styles such as skeuomorphism introduce extensive shading to give the illusion of depth, busy material textures and color palettes may distract from reading data. The influence of certain theme choices such as skeuomorphism vs. flat or semi-flat designs as well as the use of graphical decorators require further research. It is important to establish how they may support or hinder readability of data especially for watch face scenarios that require quick and accurate data readings.

Scalability: The Number of Complications and Their Complexity. For small data representations, it is intuitive to recommend that their designs are simple and should encode only a few data values or dimensions. However, it would be useful to study the encoding limits empirically in more depth. Studies could investigate two scenarios of increasing visualization complexity: (1) adding more dimensions, more data values, more encoding types while keeping the same (small) display space and (2) decreasing the display space while keeping the same level of data complexity. Some of the past studies on visualization size (e. g., [68], [77], [78], [79], [80]) have consistently shown that people prefer larger visualizations but we have also seen that participants effectively and correctly completed certain tasks with appropriate encodings at small scale [1]. In addition to questions regarding the scalability (or miniaturization) of visualizations, scalability questions also arise regarding the number of visualizations to show on watch faces. Should all data be represented with a single visualization? If not, what would be a good number to have? Both our prior survey and current review show that wearers had 3–5 complications on average, including time on their watch faces. The highest number of complications was 17. How many complications on a smartwatch display can effectively communicate with wearers needs further research. In summary, there are several avenues of scalability to explore: more data, smaller size, and more visualizations.

Specific Visualization Designs for Watch Faces. Icons are useful on smartwatches as they often label the data shown. It would be useful to study how this label functionality of an icon can be combined with the display of numerical data. Possibilities exist such as using animation, generating pictographs, or sizing icons as discussed earlier but their effectiveness has not been empirically assessed for watch faces. Simplified icons with minimal color are highly recognizable [81] and potentially readable during quick glances providing motivation for studying them further.

6.2 Smartwatch Technology and Interactivity

In the future, we will see displays of different shapes emerge for which dedicated watch face designs have to be developed. First prototypes of watchstrap displays [82] as well as curved displays [31] have emerged. Other types of embedded screens in clothing or as wristbands will emerge and we have to understand how watch faces can be designed for these non-flat displays.

An issue related to display technology is how wearers can interact with the shown content. Few interactions with visualizations on watch faces have been implemented to mitigate “fat finger problems” (e. g., Bezel Interaction [7], EdgeSelect Interaction [8]). At this point mostly simple swipes and taps are used on touch-enabled watch faces. These allow, for example, switches between different representations or time intervals. Yet, more interactions that are complex have been explored for touch interactions on desktop-sized or tablet-sized charts (see [83], [84] for a summary). If they are useful and how they can be used in the context of smartwatches when the “fat finger problem” becomes even more acute is an interesting avenue for research. In addition to smartphones, many smartwatches are equipped with a microphone, allowing people to interact with them using speech. Therefore, recent research has started to investigate how to leverage touch and speech input for the collection or exploration of personal data on mobile devices [9], [10], [85]. It would be valuable to explore further, how to leverage speech input to facilitate more fluid watch face interactions.

6.3 The Role of Context

The primary intended context of a watch face’s use needs to be considered in its graphical and interaction design. One important contextual factor is the potential movement of a wearer. Movement might lead to changing lighting conditions that can affect the readability of a watch face but movement also often entails a primary task such as driving or running. To what extent will movement affect people’s ability to read a watch face such as during sports activities? The default for some Garmin watches, for example, is to show data during exercise using large black font on a white background without any visualizations. Is this the most effective and safe way to communicate data to wearers during other primary tasks? Especially contexts with divided attention, for example, glancing while driving, require further research attention. While driving, viewers can only afford quick glances at watch faces. Visualizations in these settings are difficult to evaluate and test and future work is needed.

Another important factor is the intended task context for watch faces. While much research has centered around improving personal health through watch face representations, there needs to be more focus on the visualization challenges related to other specific tasks on smartwatch faces (see Sec. 2.1). We also saw commercial watch faces target contexts of use that we had not seen in research such as entertainment, festival, or military usage. Carpendale et al. [14]

showed that with dedicated ideation exercises watch faces could be envisioned that target specific usage contexts such as sightseeing in their case. Digital watch faces are easy to switch and it would be interesting to study the impact of dedicated but changing watch faces on wearers.

7 CONCLUSION

We presented a systematic review and design space for embedding visualizations into watch faces. The design space is grounded in the collection and analysis of properties of actual watch faces. Our holistic approach looked at smartwatches not just as data displays but also as a personal accessory for which visualizations are just one of many components that need to fit within a larger visual ecosystem. This led us to consider, for the first time, dimensions like the UI style and visual themes that may have an impact on visualization design, but have not been part of visualization design considerations in smartwatch research. We discuss the interplay of these dimensions and the choices available to visualization designers, as well as pitfalls and challenges when it comes to designing visualizations for such a personal use. Our research agenda highlights open opportunities both for visualization designers and for empirical research.

ACKNOWLEDGMENTS

In Fig. 1 Smartwatch face examples come from Facer [53]). From left to right: a) Pixel-like Analog / Digital (clayton), b) Big step 6000 (MB-Watch), c) B# – Open Heart (B Sharp Watches), d) Comic Pro! (Round or Square; Roch: Platinum Designs), e) Legion – ctOS (Watch Dogs), f) MOD–486 Weather Watch (Michael O’Day), g) Fall Mandala (Linlay Designs), h) Lovely (Cokanut).

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REFERENCES

- [1] T. Blascheck, L. Besançon, A. Bezerianos, B. Lee, and P. Isenberg, “Glanceable visualization: Studies of data comparison performance on smartwatches,” *IEEE TVCG*, vol. 25, no. 1, pp. 630–640, 2019.
- [2] W. Jackson and Pao, *SmartWatch Design Fundamentals*. Springer, 2019.
- [3] A. Islam, A. Bezerianos, B. Lee, T. Blascheck, and P. Isenberg, “Visualizing information on watch faces: A survey with smartwatch users,” in *Proc. IEEE Visualization, Short Papers*, 2020, pp. 156–160.
- [4] C. Min, S. Kang, C. Yoo, J. Cha, S. Choi, Y. Oh, and J. Song, “Exploring current practices for battery use and management of smartwatches,” in *Proc. of Wearable Computers*. ACM, 2015, pp. 11–18.
- [5] M. T. Raghunath and C. Narayanaswami, “User interfaces for applications on a wrist watch,” *Personal Ubiquitous Comput.*, vol. 6, no. 1, pp. 17–30, 2002.
- [6] A. Kamišalić, I. Fister, M. Turkanović, and S. Karakatić, “Sensors and functionalities of non-invasive wrist-wearable devices: A review,” *Sensors*, vol. 18, no. 6, p. 1714, 2018.
- [7] A. Neshati, B. Rey, A. S. Mohommed Faleel, S. Bardot, C. Latulipe, and P. Irani, “Bezelglide: Interacting with graphs on smartwatches with minimal screen occlusion,” in *Proc. of Human Factors in Computing Systems*. ACM, 2021.
- [8] A. Neshati, A. Salo, S. A. Faleel, Z. Li, H.-N. Liang, C. Latulipe, and P. Irani, “EdgeSelect: Smartwatch data interaction with minimal screen occlusion,” in *Proc. of the Conference on Multimodal Interaction*. ACM, 2022, pp. 288–298.
- [9] Y.-H. Kim, D. Chou, B. Lee, M. Danilovich, A. Lazar, D. E. Conroy, H. Kacorri, and E. K. Choe, “MyMove: Facilitating older adults to collect in-situ activity labels on a smartwatch with speech,” in *Proc. of Human Factors in Computing Systems*. ACM, 2022.
- [10] B. Rey, B. Lee, E. K. Choe, and P. Irani, “Investigating in-situ personal health data queries on smartwatches,” *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, vol. 6, no. 4, pp. 1–19, 2023.
- [11] S. Pizza, B. Brown, D. McMillan, and A. Lampinen, “Smartwatch in vivo,” in *Proc. of Human Factors in Computing Systems*. ACM, 2016, pp. 5456–5469.
- [12] F. Amini, K. Hasan, A. Bunt, and P. Irani, “Data representations for in-situ exploration of health and fitness data,” in *Proc. of Pervasive Computing Technologies for Healthcare*. ACM, 2017, pp. 163–172.
- [13] A. Suciuc and J. Larsen, “Active self-tracking and visualization of subjective experience using VAS and time spirals on a smartwatch,” in *Proc. of the Data Visualization on Mobile Devices Workshop held at the Conference on Human Factor in Computing Systems*, 2018.
- [14] S. Carpendale, P. Isenberg, C. Perin, T. Blascheck, F. Daneshzand, A. Islam, K. Currier, P. Buk, V. Cheung, L. Quach, and L. Vermette, “Mobile Visualization Design: An Ideation Method to Try,” in *Mobile Data Visualization*. Chapman and Hall/CRC, 2021, pp. 241–261.
- [15] R. Gouveia, F. Pereira, E. Karapanos, S. A. Munson, and M. Hassenzahl, “Exploring the design space of glanceable feedback for physical activity trackers,” in *Proc. of Pervasive and Ubiquitous Computing*. ACM, 2016, pp. 144–155.
- [16] F. L. Cibrian, K. D. Lakes, A. Tavakoulia, K. Guzman, S. Schuck, and G. R. Hayes, *Supporting Self-Regulation of Children with ADHD Using Wearables: Tensions and Design Challenges*. ACM, 2020, pp. 1–13.
- [17] D. Albers, M. Correll, and M. Gleicher, “Task-driven evaluation of aggregation in time series visualization,” in *Proc. of the Conference on Human Factors in Computing Systems*. ACM, 2014, pp. 551–560.
- [18] R. Gouveia, E. Karapanos, and M. Hassenzahl, “How do we engage with activity trackers? a longitudinal study of habito,” in *Proc. of Pervasive and Ubiquitous Computing*. ACM, 2015, pp. 1305–1316.
- [19] A. Visuri, Z. Sarsenbayeva, N. van Berkel, J. Goncalves, R. Rawassizadeh, V. Kostakos, and D. Ferreira, “Quantifying sources and types of smartwatch usage sessions,” in *Proc. of Human Factors in Computing Systems*. ACM, 2017, pp. 3569–3581.
- [20] T. Blascheck, L. Besançon, A. Bezerianos, B. Lee, A. Islam, T. He, and P. Isenberg, “Studies of part-to-whole glanceable visualizations on smartwatch faces,” in *The IEEE Pacific Visualization Symposium (PacificVis)*, 2023, pp. 187–196.
- [21] K. Lyons, “Visual parameters impacting reaction times on smartwatches,” in *Proc. Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, 2016, pp. 190–194.
- [22] S. M. Neis and M. I. Blackstun, “Feasibility analysis of wearables for use by airline crew,” in *Proc. of the IEEE/AIAA Digital Avionics Systems Conference*. IEEE, 2016, pp. 1–9.
- [23] Y. Chen, “Visualizing Large Time-series Data on Very Small Screens,” in *Short Papers of the European Conference on Visualization (EuroVis)*. The Eurographics Association, 2017.
- [24] A. Neshati, Y. Sakamoto, L. C. Leboe-McGowan, J. Leboe-McGowan, M. Serrano, and P. Irani, “G-sparks: Glanceable sparklines on smartwatches,” in *Proc. Graphics Interface*. Canadian Information Processing Society, 2019, pp. 23–1.
- [25] A. Neshati, F. Alallah, B. Rey, Y. Sakamoto, M. Serrano, and P. Irani, “SF-LG: Space-filling line graphs for visualizing interrelated time-series data on smartwatches,” in *Proc. of the International Conference on Mobile Human-Computer Interaction*. ACM, 2021, pp. 1–13.
- [26] Ö. Pektaş, M. Köseoğlu, M. Muzny, G. Hartvigsen, and E. Årsand, “Design of an android wear smartwatch application as a wearable interface to the diabetes diary application,” *Academic Platform - Journal of Engineering and Science*, vol. 9, no. 1, pp. 126–133, 2021.
- [27] J. Niess, K. Knaving, A. Kolb, and P. W. Woźniak, “Exploring fitness tracker visualisations to avoid rumination,” in *International Conference on Human-Computer Interaction with Mobile Devices and Services*. ACM, 2020.
- [28] H. Havlucu, I. Bostan, A. Coskun, and O. Özcan, “Understanding the lonesome tennis players: Insights for future wearables,” in *Proc. of the Conference on Human Factors in Computing Systems*. ACM, 2017, pp. 1678–1685.
- [29] A. Schiewe, A. Krekhov, F. Kerber, F. Daiber, and J. Krüger, “A study on real-time visualizations during sports activities on smartwatches,” in *Proc. of the International Conference on Mobile and Ubiquitous Multimedia*, 2020, pp. 18–31.
- [30] A. Esakia and L. Kotut, “Smartwatch-centered design and development in mobile computing classes,” in *Proc. of the Frontiers in Education Conference*. IEEE, 2020, pp. 1–7.

- [31] K. Klamka and R. Dachsel, "Bendable color ePaper displays for novel wearable applications and mobile visualization," in *Proc. of User Interface Software and Technology*. ACM, 2021, pp. 6–10.
- [32] C. Xu and K. Lyons, "Shimmering smartwatches: Exploring the smartwatch design space," in *Proc. of the International Conference on Tangible, Embedded, and Embodied Interaction*. ACM, 2015, pp. 69–76.
- [33] A. Islam, R. Aravind, T. Blascheck, A. Bezerianos, and P. Isenberg, "Preferences and effectiveness of sleep data visualizations for smartwatches and fitness bands," in *Proc. of Human Factors in Computing Systems*. ACM, 2022.
- [34] A. Neshati, Y. Sakamoto, and P. Irani, "Challenges in displaying health data on small smartwatch screens," in *Improving Usability, Safety and Patient Outcomes with Health Information Technology*, F. Lau, J. Bartle-Clar, G. Bliss, E. Borycki, K. Courtney, A. M.-H. Kuo, A. Kushniruk, H. Monkman, and A. Roudsari, Eds. IOS Press, 2019, pp. 325–332.
- [35] K. Hänsel, A. Alomainy, and H. Haddadi, "Large scale mood and stress self-assessments on a smartwatch," in *Proc. of Pervasive and Ubiquitous Computing*. ACM, 2016, pp. 1180–1184.
- [36] S. Zenker and S. Hobert, "Design and implementation of a collaborative smartwatch application supporting employees in industrial workflows," in *Proc. of the European Conference on Information Systems*. Association for Information Systems Electronic Library, 2019, pp. 1–16.
- [37] C. Gkourmelos, P. Karagiannis, N. Kousi, G. Michalos, S. Koukas, and S. Makris, "Application of wearable devices for supporting operators in human-robot cooperative assembly tasks," *Procedia CIRP*, vol. 76, pp. 177–182, 2018.
- [38] Y. Bernaerts, M. Druwé, S. Steensels, J. Vermeulen, and J. Schöning, "The office smartwatch: Development and design of a smartwatch app to digitally augment interactions in an office environment," in *Companion Publication, Designing Interactive Systems*. ACM, 2014, pp. 41–44.
- [39] W. K. Bodin, D. Jaramillo, S. K. Marimekala, and M. Ganis, "Security challenges and data implications by using smartwatch devices in the enterprise," in *Proc. of the International Conference Expo on Emerging Technologies for a Smarter World*. IEEE, 2015, pp. 1–5.
- [40] B. G. Lee, J.-H. Park, C. C. Pu, and W.-Y. Chung, "Smartwatch-based driver vigilance indicator with kernel-fuzzy-c-means-wavelet method," *IEEE Sensors Journal*, vol. 16, no. 1, pp. 242–253, 2016.
- [41] G. Li, B.-L. Lee, and W.-Y. Chung, "Smartwatch-based wearable eeg system for driver drowsiness detection," *IEEE Sensors Journal*, vol. 15, no. 12, pp. 7169–7180, 2015.
- [42] F. Grioui and T. Blascheck, "Study of heart rate visualizations on a virtual smartwatch," in *Proc. of Virtual Reality Software and Tech*. ACM, 2021.
- [43] S. Langer, D. Dietz, and A. Butz, "Towards risk indication in mountain biking using smart wearables," in *Extended Abstracts, Conference on Human Factors in Computing Systems*. ACM, 2021, pp. 1–7.
- [44] A.-R. Asadi, "iParallel: A smartwatch-based serious game for organizational learning," in *Proc. of the International Serious Games Symposium*. IEEE, 2020, pp. 68–73.
- [45] D. Wenig, J. Schöning, B. Hecht, and R. Malaka, "Stripemaps: Improving map-based pedestrian navigation for smartwatches," in *Proc. of the Conf. on Human-Computer Interaction with Mobile Devices and Services*. ACM, 2015, pp. 52–62.
- [46] M. Perebner, H. Huang, and G. Gartner, "Applying user-centred design for smartwatch-based pedestrian navigation system," *Journal of Location Based Services*, vol. 13, no. 3, pp. 213–237, 2019.
- [47] S. Gedicke, A. Bonerath, B. Niedermann, and J. Haurert, "Zoomless maps: External labeling methods for the interactive exploration of dense point sets at a fixed map scale," *IEEE Transactions on Visualization & Computer Graphics*, vol. 27, no. 02, pp. 1247–1256, feb 2021.
- [48] M. Doan, F. L. Cibrián, A. Jang, N. Khare, S. Chang, A. Li, S. Schuck, K. D. Lakes, and G. R. Hayes, "CoolCraig: A smart watch/phone application supporting co-regulation of children with ADHD," in *Extended Abstracts, Conference on Human Factors in Computing Systems*. ACM, 2020, pp. 1–7.
- [49] M. Kosanović and S. N. Stosovic, "The concept for the "smart home" controlled by a smartwatch," *Facta universitatis. Series electronics and energetics*, vol. 31, pp. 389–400, 2018.
- [50] M. Agnihotri, R. Upadhyaya, K. Kenna, and C.-D. Chiang, "Rist: An interface design project for indoor navigation," in *Proc. of Communications in Computer and Information Science*, vol. 714. Springer, 2017, pp. 327–334.
- [51] W.-C. Wang, C.-C. Chen, and T.-H. Chiu, "An initial exploration into the design of visualized interfaces to help children search for books using smartwatches," in *Proc. of the IFLA WLIC – Poster*, 2017.
- [52] M. van Rossum, "Patient empowerment via a smartwatch activity coach application: Let the patient gain back control over their physical and mental health condition," Master's thesis, TU Delft, 2020, last visited: February, 2022. [Online]. Available: <http://resolver.tudelft.nl/uuid:472a369f-0915-4486-85d0-40323932e3a9>
- [53] Little Labs, Inc., "Facer—the largest watch face platform for apple watch, wearos, and tizen." <https://www.facer.io/>, accessed: January, 2023.
- [54] I. D. Foundation, "Skeuomorphism," <https://www.interaction-design.org/literature/topics/skeuomorphism/>, accessed: January, 2023.
- [55] K. Spiliotopoulos, M. Rigou, and S. Sirmakessis, "A comparative study of skeuomorphic and flat design from a ux perspective," *Multimodal Technologies and Interaction*, vol. 2, no. 2, pp. 1–21, 2018.
- [56] T. Munzner, "Developing design spaces for visualization, stanford HCI seminar talk slides," <http://www.cs.ubc.ca/~tmm/talks.html#stanf22>, talk held on March 4th, 2022. Slides last visited: March, 2022.
- [57] J. Vanderdonck, S. Bouzit, G. Calvary, and D. Chêne, "Exploring a design space of graphical adaptive menus: Normal vs. small screens," *ACM Trans. Interact. Intell. Syst.*, vol. 10, no. 1, 2019.
- [58] Android developer guides, "Watch face complications," <https://developer.android.com/training/wearables/watch-faces/complications/>, accessed: March, 2022.
- [59] Apple Developer Documentation, "Watch faces," <https://developer.apple.com/design/human-interface-guidelines/watch-faces/>, accessed: July, 2023.
- [60] L. Angelini, M. Caon, S. Carrino, L. Bergeron, N. Nyffeler, M. Jean-Mairet, and E. Mugellini, "Designing a desirable smart bracelet for older adults," in *Proc. of Pervasive and Ubiquitous Computing Adjunct Publication*. ACM, 2013, pp. 425–434.
- [61] S. Schirra and F. R. Bentley, "'it's kind of like an extra screen for my phone": Understanding everyday uses of consumer smart watches," in *Extended Abstracts, Conference on Human Factors in Computing Systems*. ACM, 2015, pp. 2151–2156.
- [62] P. Goffin, J. Boy, W. Willett, and P. Isenberg, "An exploratory study of word-scale graphics in data-rich text documents," *IEEE TVCG*, vol. 23, no. 10, pp. 2275–2287, 2017.
- [63] F. Beck and D. Weiskopf, "Word-sized graphics for scientific texts," *IEEE TVCG*, vol. 23, no. 6, pp. 1576–1587, 2017.
- [64] J. Fuchs, P. Isenberg, A. Bezerianos, and D. Keim, "A systematic review of experimental studies on data glyphs," *IEEE TVCG*, vol. 23, no. 7, pp. 1863–1879, 2017.
- [65] T. Munzner, *Visualization analysis and design*. CRC press, 2014.
- [66] W. Aigner, S. Miksch, H. Schumann, and C. Tominski, *Visualization of Time-Oriented Data*, 1st ed. Springer, 2011.
- [67] P. Dragicevic and S. Huot, "SpiraClock: A continuous and non-intrusive display for upcoming events," in *Extended Abstracts, Conference on Human Factors in Computing Systems*. ACM, 2002, pp. 604–605.
- [68] C. G. Healey and A. P. Sawant, "On the limits of resolution and visual angle in visualization," *ACM Transactions on Applied Perception*, vol. 9, no. 4, 2012.
- [69] P. Isenberg, "Micro visualizations: Design and analysis of visualizations for small display spaces," Habilitation, Université Paris-Saclay, 2021. [Online]. Available: <https://hal.inria.fr/tel-03584024>
- [70] Y. Zhong, T. Isenberg, and P. Isenberg, "Black-and-White Textures for Visualization on E-ink Displays," *IEEE Conference on Visualization – Poster*, 2020.
- [71] S. Few, "There's nothing mere about semantics," <https://www.perceptualedge.com/blog/?p=2793>, Blog Post.
- [72] A. Sarikaya, M. Correll, L. Bartram, M. Tory, and D. Fisher, "What do we talk about when we talk about dashboards?" *IEEE TVCG*, vol. 25, no. 1, pp. 682–692, 2019.
- [73] B. Bach, E. Freeman, A. Abdul-Rahman, C. Turkey, S. Khan, Y. Fan, and M. Chen, "Dashboard design patterns," *IEEE TVCG*, pp. 1–11, 2022.
- [74] R. Zehrung, L. Huang, B. Lee, and E. K. Choe, "Investigating opportunities to support kids' agency and well-being: A review of kids' wearables," *arXiv preprint arXiv:2104.05979*, 2021.
- [75] E. Tufte, *Envisioning Information*. Graphics Press, 1990.
- [76] S. Bateman, R. L. Mandryk, C. Gutwin, A. Genest, D. McDine, and C. Brooks, "Useful junk? The effects of visual embellishment on comprehension and memorability of charts," in *Proc. of Human Factors in Computing Systems*. ACM, 2010, pp. 2573–2582.
- [77] X. Cai, K. Efsthathiou, X. Xie, Y. Wu, Y. Shi, and L. Yu, "A study of the effect of doughnut chart parameters on proportion estimation accuracy," *Computer Graphics Forum*, vol. 37, no. 6, pp. 300–312, 2018.
- [78] W. Javed, B. McDonnell, and N. Elmqvist, "Graphical perception of multiple time series," *IEEE TVCG*, vol. 16, no. 6, pp. 927–934, 2010.
- [79] J. Heer, N. Kong, and M. Agrawala, "Sizing the horizon: The effects of chart size and layering on the graphical perception of time series visualizations," in *Proc. of Human Factors in Computing Systems*. ACM, 2009, pp. 1303–1312.

- [80] C. Perin, R. Vuillemot, and J.-D. Fekete, “SoccerStories: A kick-off for visual soccer analysis,” *IEEE TVCG*, vol. 19, no. 12, pp. 2506–2515, 2013.
- [81] S. Haroz, R. Kosara, and S. L. Franconeri, “Isotype visualization: Working memory, performance, and engagement with pictographs,” in *Proc. of Human Factors in Computing Systems*. ACM, 2015, pp. 1191–1200.
- [82] K. Klamka, T. Horak, and R. Dachsel, “Watch+strap: Extending smartwatches with interactive strapdisplays,” in *Proc. of Human Factors in Computing Systems*. ACM, 2020, pp. 1–15.
- [83] B. Lee, A. Srinivasan, P. Isenberg, and J. Stasko, “Post-wimp interaction for information visualization,” *Foundations and Trends® in Human-Computer Interaction*, vol. 14, no. 1, pp. 1–95, 2021.
- [84] M. Brehmer, B. Lee, J. Stasko, and C. Tominski, “Interacting with visualization on mobile devices,” in *Mobile Data Visualization*. Chapman and Hall/CRC, 2021, pp. 67–110.
- [85] Y.-H. Kim, B. Lee, A. Srinivasan, and E. K. Choe, “Data@hand: Fostering visual exploration of personal data on smartphones leveraging speech and touch interaction,” in *Proc. of Human Factors in Computing Systems*. ACM, 2021, pp. 1–17.



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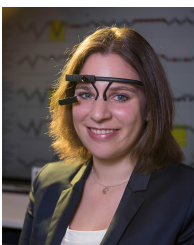
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Fig. 7: Four examples of smartwatch faces using our design space dimensions to describe them.