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CHAPTER 2

Responsive Visualization Design for Mobile Devices

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WITH the proliferation of mobile devices, people can now interact with data visualization on smartphones, tablets, and smartwatches. Although these new devices offer the opportunity to visualize data in mobile contexts, most visualization techniques used in practice were originally designed with desktop displays in mind. These desktop-oriented techniques are often ill-suited for mobile devices due to differences and restrictions in display size, aspect ratio, and interaction capabilities. Furthermore, mobile usage is contingent upon many contextual aspects, such as one-handed interaction, unstable movement, or noisy surroundings. The combination of these factors require that data visualization design must be *responsive* to device constraints and dynamic usage contexts.

This chapter is about *responsive data visualization design* for *mobile devices*. We use the term *responsive* to describe aspects of visualization that adapt automatically to various factors, such as changed device characteristics, environment, usage context, data, or user requirements. Given the theme of this book, we focus on mobile devices, although it should be noted that responsive visualization design is also applicable to non-mobile devices, such as PC displays of varying size, tabletop displays, and large wall- or projector-based displays. We discuss aspects of responsive mobile data visualization as well as its relation to existing visualization concepts in Section 2.1, before contrasting it to responsive *web* design in Section 2.2. Section 2.3 summarizes the types of change that visualization must respond to and how they can be sensed on mobile devices. We then review ten responsive visualization design strategies in Section 2.4, including adaptations of scale, layout, and visual encoding as well as attentional cues and specific interactions. Finally, Section 2.5 describes possible future research directions pertaining to responsive visualization design for mobile devices and beyond.

2.1 CONTEXT

Over the course of the last decade, a new class of mobile devices has become ubiquitous in our daily lives. A key characteristic of these devices is their mobility, allowing people to access visualized information anywhere and anytime. However, visualizing the information appropriately remains a challenge, due in part to how mobile devices vary considerably in their display and interaction capabilities, even within the same device class. For example, display sizes of tablets can range from 4.8 to 13 inches. Smartphones typically have an aspect ratio of 16:9, but there are also phones with aspect ratios of 3:2 or 21:9. Even the familiar form factor of rectangular displays can no longer be taken for granted with the advent of circular smartwatches. The heterogeneity of mobile devices makes it virtually impossible to design one-size-fits-all visualization solutions. Embracing a responsive design mindset is a way to keep development cost down while catering to the needs of different devices and usage contexts. We will come back to this idea of "Develop Once, Deploy to Many" in Section 2.5 of our chapter.

Moreover, an increase in mobility and connectivity means that it is possible to use a mobile device across many diverse contexts that are quite unlike those envisioned or typically considered in visualization design. Interactive visualization designed for mobile usage might be used on a bumpy bus ride, in a relaxed position on the couch, on the go while leaving the office, under bright sunlight, or in the dim light of a crowded elevator. In all of these situations, the visualization must allow people to satisfy their information needs and fulfill their interaction intent. Unfortunately, contemporary visualization design is usually optimized for only a small number of contexts. For example, news graphics teams typically produce variants of a visualization for desktops, tablets, and phones instead of creating a single responsive design [47, 79]. This is in contrast to the develop-once idea mentioned before.

To account for the different device properties and usage scenarios, we must design visualizations that adapt automatically. This realization has been apparent for several years in discussions pertaining to *scalability* and particularly those about display scalability [89]. This realization gained momentum with the rise of *responsive web design*, where web pages adapt their layout automatically to the browser viewport. However, while it is now common for web pages to follow a responsive philosophy, for visualization design often no adaptations are applied at all. Recently, Wu et al. [100] studied various visualizations and found that over 73% of them faced at least one issue when being displayed on mobile devices. As a solution, Wu et al. proposed a framework that automatically fixes the detected issues. An alternative to fixing broken visualizations at run time is to implement responsive behavior already at design time, which will allow for incorporating more suitable strategies.

To recap, *responsiveness* denotes the ability of a visualization design to adapt to changing contexts. Responsive behavior can be triggered both by explicit changes invoked by a user or by implicit changes sensed in the environment. For example, a stock ticker mobile application might provide a more detailed chart when the user rotates the device from portrait into landscape mode. Or consider how a personal fitness application might automatically activate a special mode with increased button and font sizes when it detects usage while in motion, for example, when riding a bus.

This chapter discusses responsiveness for mobile data visualization in greater depth. The visualization research and practitioner communities provide a few starting points for this topic, but there remains a clear need for a structured investigation of *what* might trigger automatic visualization adaptation, as well as *how* the adaptation can manifest.

2.2 RESPONSIVE DESIGN VS. RESPONSIVE VISUALIZATION DESIGN

Despite the web design community's recent embrace of responsive and mobile-first design approaches, the visualization community has yet to establish responsive design principles to a similar extent. This is not to say that the visualization community has ignored mobile usage scenarios, as many visualization techniques have been developed for smartphone, tablet, and watch interfaces (quite a few of these are profiled throughout this book). However, these existing techniques tend to focus on single contexts rather than on varied and dynamic usage contexts. Existing literature on responsive visualization design [51, 46, 57] is primarily concerned with implementation aspects and how responsiveness can be achieved using web technologies in particular. However, systematic examinations from a conceptual perspective are rare [21, 36] or predate the smartphone era [34, 22, 71].

Over the past two decades, the fields of mobile user interface design and web design have faced an increasing heterogeneity of devices and capabilities. The sheer number of possibilities quickly made it impossible to create designs tailored for each platform and thus a more adaptive approach was deemed necessary. To realize this, designers had to relinquish some control over specificity of their applications.

In 2010, three years after the release of the first iPhone, Ethan Marcotte attracted much discussion with his *"Responsive Web Design"* blog post [63], in which he introduced three pillars of responsiveness:

- **Fluid grids**: relative grid specifications based on percentages rather than pixels and changing of grid layouts based on interface constraints (such as converting a three-column layout to a single-column layout).
- **Flexible images**: the percentage-based sizing and automatic creation, caching, and delivery of device-appropriate images.
- **Media queries**: a part of the CSS specification that allows web apps to inspect the physical characteristics of the device.

While one might argue that data visualized on a mobile display should be considered as an image with respect to responsive web design [64], this argument falls short. A visualization is more than just an image: it is a complex and structured object in itself. It differs from an image in terms of composition, data-dependency, interactivity, and scalability.

Consider for example the inner composition of a chart. Simply scaling down or changing the aspect ratio of a chart is not merely a technical question of size and resolution, but rather that the content and representation need to be carefully adapted. Let's take a simple bar chart as an example; while the bars themselves might be easily scaled down, the same strategy cannot be applied for data or axes labels to the same extent. For these elements, adjustments such as repositioning, abbreviation, or partial omission might be more suitable.

Also unlike images, interactivity often plays a vital role in visualization [90]. The visualization community has developed countless techniques for selecting, annotating, aggregating, filtering, and partitioning data points, as well as techniques for navigating along data dimensions and modifying visual encoding channels [68]. To achieve responsive visualization design, these interaction techniques must also be adapted in addition to the visual representation.

Visualization is unlike image content also in that the visual representation is explicitly determined by the underlying data. Particular combinations of visual representation and dataset may not be amenable for displays of varying size.

This brings to mind the topic of *scalability*, which is one of the key challenges of visual analytics research [89]. This aspect not only concerns questions of visual representation that depend on the available screen real estate or the number of visual elements to display. It is also very much related to other device constraints such as the often limited processing power or lower network bandwidth of mobile devices. These can make it hard, for example, to store large datasets or run complex data analytics pipelines on the device itself.

We reiterate that *responsive visualization design* cannot be thought of in the same way as images are treated in responsive web design. Responsive visualization must respond to various changes and it must adapt in one or more of the various ways described below. While many of the approaches from responsive web design are applicable in responsive visualization design, we acknowledge the roles of data and the separable components of visualization content.

Responsive mobile visualization is the synthesis of *responsive design* and *visualization design for mobile devices*. Körner's [57] definition of the former implies an adaptation of appearance and behavior, including interaction, to a user's device. As discussed in Chapter 1, *mobile visualization design* encompasses several criteria, including the size and the mobility of the data display and reaction to movement.

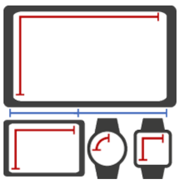
In bringing responsive design and mobile visualization together, we address interactive visual data representations that adapt their appearance and behavior to changing factors. This means that responsive mobile visualization must account for changes in data (e.g., small vs. large data sets), the user with their visualization and interaction literacy, the device type and its capabilities, its usage (e.g., whether it is held in portrait or landscape mode), and the environment (e.g., comfortable home use vs. use on a shaky bus).

Although we consider responsive mobile visualization broadly, we focus on devices ranging from smartwatches to smartphones and tablets. We do not address augmented or virtual reality devices such as stereoscopic and head-mounted devices, which are discussed in Chapter 4. Nor do we discuss responsive visualization design for tabletop- and wall-based displays due to their limited mobility aspects. Lastly, collaborative usage scenarios are out of scope as well.

2.3 FACTORS IMPACTING VISUALIZATION DESIGN ON MOBILE DEVICES

As stated before, responsive mobile visualization must be able to adapt to a variety of factors, such as device properties, usage context, or data characteristics. Accordingly, we categorize them into five types of factors: device factors, usage factors, environmental factors, data factors, and human factors. All these factors can significantly impact how well a person can perceive and interactively analyze the visualization content and thus the data. Therefore, it is necessary to examine in detail what these various factors are and how they can be sensed or inferred in the context of responsive visualization design.

2.3.1 Device Factors



Although our focus is on smartwatches, smartphones, and tablets, this is nonetheless a broad spectrum of devices. The most visually prominent difference across these devices is **display size**. Display sizes can range from only dozens of pixels up to resolutions similar to desktop devices. Notably, "size" can be considered in two ways: as a virtual unit expressed in pixels and as a physical unit in centimeters. In responsive web design, often only the virtual size is considered. However, in visualization design, we argue that the physical size and the pixel density is highly relevant. Similarly, the **aspect ratio** of a display can differ significantly, even within a usage session, such as by rotating a device from landscape to portrait mode. Moreover, many smartwatch displays now incorporate non-rectangular shapes. As many visualizations are sensitive with respect to size and aspect ratio, the device characteristics can prove to be challenging when bringing visualizations to them.

The current approach to handle different display sizes is using breakpoints: hard-coded width values at which content is adapted in some way; between these breakpoints, the content is simply scaled to fit the width [64]. For visualization design, this strategy might not be sufficient to avoid negative effects with respect to readability and graphical perception [16, 97]. To optimize for graphical perception, designers must consider other device factors such as color support, contrast, or refresh rate. Such factors are particularly important when considering devices with alternative display technologies such as e-ink [48, 56].

The **interaction modalities** supported by mobile devices are also relevant to responsive visualization design: a different modality might require a different interaction mechanism to be implemented. As the default, current smartphones support touchscreen input. While being a very direct form of interaction, touch is prone to the so-called *fat-finger problem* [85] and can hinder the interaction with small elements. Similarly, the lack of mouse buttons (e.g., for right click) makes it necessary to think about alternatives, with touch gestures or pressure-sensitive touch being common ones. Pen- and stylus-based interaction has also become more prominent in recent years with devices such as the Samsung Galaxy Note or the Apple iPad Pro. Pens can offer higher precision allowing for interaction even with fine details in a visualization. In addition to on-screen interactions, mobile devices offer further input modalities such as hardware buttons (a camera button, a back button, or rotatable controls for watches), spatial interaction (such as tilting recognized through built-in sensors), or speech input. A more complete overview of the interaction with mobile devices is given in Chapter 3. For the purposes of our discussion, it suffices to say that when a device's most prominent input modality is atypical (particular when not an on-surface input), adaptations to the visualization design will likely be required.

Finally, the devices' specific **hardware and software** can add limitations to a visualization interface as well. Supported software features defined by the mobile operating system and, particularly for web visualizations, the mobile web browser can notably differ between devices. Similarly, connectivity and performance-related hardware components (such as the CPU, GPU, RAM, storage) can influence the speed of interaction as well as how much content can be loaded and rendered. These factors may also impact battery life differently across devices, where high power consumption will drain the battery until a point at which the operating system will limit the performance to extend battery life.

2.3.2 Usage Factors

When using a mobile device, interaction is no longer only shaped by device factors but also by how and in which **posture** a person is using the device. With desktop computers, the usage is consistent: one is facing the monitor and typically using mouse and keyboard. In contrast, mobile devices can be used in a variety of ways: either hand held, placed on a table, or even body-worn as with smartwatches; while sitting, standing, or lying down; and with one or two hands [8, 30, 31]. In consequence, the viewing angle, orientation, and distance to the display can differ, which likely affects readability of the visualized content.

Further, whether the device is lying flat on a surface, wrist mounted, or hand held will affect the **interaction style** and potentially the precision of a person. On a steady device, small marks can be selected more precisely than on a handheld device, which can slightly move when interacting. The way in which we hold a device also determines which parts of the interface or visualization are easy to reach. For example, when holding and using the device with just one hand, content in the opposite display corner of the hand is typically harder to access [31]. In general, the usage type is closely coupled to device factors such as size, weight, and interaction modalities [32, 102]. Switching from a one-handed usage to a two-handed usage often comes with rotating the device from landscape to portrait orientation, affecting the aspect ratio available for the visualization content.

2.3.3 Environmental Factors

Beyond the control of a person using a mobile device are changes in their surrounding environment. These changes can also impact interaction with visualization content directly as well as indirectly via changes in usage as responses to changes in the environment. For instance, consider that one's environment can be in motion when **on-the-go**, such as when traveling inside a bus, train, or car. Jostling around within a busy train can reduce one's ability to read or interact with the visualization. Further, one might be transitioning to one-handed usage if the other hand is holding on to a safety bar during the ride. In addition to movement, crowdedness can also impose limitations. For example, voice-based input and auditory output are hardly feasible in crowded spaces.

For direct impacts of the surrounding on the visualization content consider the differences between **indoor and outdoor environments**. In outdoor environments, the lighting situation is dynamic and often problematic for visual perception, such as direct sunlight or dark surroundings in the early morning; both situations may require the display brightness to be adjusted. Variable and insufficient lighting affects the readability of visualizations, especially concerning hue and contrast perception [95]. Other encoding channels might be used to compensate for these deficiencies, or an information display could be simplified for mobile and outdoor environments.

2.3.4 Data Factors

As for visualization design in general, the **structure and size** of a dataset determines which visualization techniques are appropriate [91]. In particular, when displaying large amounts of data, one must consider the viewer's ability to read, understand, and interact with the visualization. These challenges are further amplified with mobile devices and their often small screen sizes. For instance, visualization of many data points as individual marks can lead to rendering performance issues and a lagging interface on a mobile device. At the same time, selecting such marks can also become challenging due to the reduced precision with touch input [94] or when marks are overlapping.

Similarly, transferring large amounts of data via mobile data connections has also an impact on performance. As loading the whole dataset may require too much time, it is possible to subsequently load chunks or only aggregated data with detailed information only being loaded on demand as in *progressive* visual data analysis approaches [6, 35]. However, as the quality of mobile data connections may degrade during a session, loading additional information might not be possible later on.

2.3.5 Human Factors

Finally, the person using the mobile device can also contribute constraints to the visualization design. Levels of visualization literacy, subject matter knowledge, attention span, and motivation vary tremendously between people; individuals also learn and change over time. For instance, one may be more motivated to interact with own personal health or finance data via a mobile device than with court case data from a remote county. It can therefore be helpful to think in terms of a person's goals or tasks. For example, one might want to casually browse through a dataset, look up a specific aspect or value, or compare multiple entities. According to Brehmer and Munzner [17], such characterizations of tasks can explain *why* a person requires visualization, and the visualization design must answer *how* a person can complete the tasks using the offered visual encodings and interactions.

An elaborate visualization design may be impractical for some combinations of user and content, though the same design may be appropriate for other combinations or after an initial learning period has elapsed. While a deeper discussion of individual differences in visualization literacy, attention span, motivation, and expertise are beyond the scope of this chapter, it is nevertheless helpful to consider these factors during the process of responsive visualization design.

2.3.6 Sensing & Inferring Multiple Factors

Responsive visualization design for mobile devices requires a way to infer the factors described thus far. Contemporary mobile devices can detect a surprising amount of information relating to these factors. Many device properties, such as the display size, pixel density, and available interaction modalities can be accessed via calls to the operating system or mobile web browser. These can also include WiFi, Bluetooth, and cellular network signal indicators that report the type and strength of network connections available to the device.

In addition, there are a variety of sensors available that can detect changes in the device's usage or environment [45]. Motion and position sensors (e.g., accelerometer, gyroscope, gravity sensor, geomagnetic field sensor) can detect the change of velocity and the relative orientation of the device. Thus, these can indicate if a device is placed on a surface or is handheld, as well as in which posture and orientation it is used. Some devices also offer pressure sensors indicating the amount of pressure one is applying to the touchscreen or on the sides of the device. Both can also be used to detect certain usage styles such as one-handed or two-handed usage.

Today's devices can also sense environmental factors. Ambient light sensors detect the intensity of the light falling into the screen, thus, indicating how well content can still be read and if adjustments of color themes or screen brightness could be beneficial. Additionally, the clock of the device can also be used to adapt visualization content for different times of the day, such as night modes in wayfinding apps. Location sensors such as GPS can calculate the location of the device, which can then be used to load further information on the individuals' surroundings (e.g., on-campus, suburban area, crowded space). In combination with WiFi signals, the location can be inferred more precisely, particularly when indoors. Besides image and video capture, the cameras of devices allow for object, bar/QR code, and face detection or—with depth cameras—for capturing the room properties as well. These can further characterize the surroundings and, for example, indicate if other persons are glancing at the content.

Finally, mobile devices can provide indicators of human factors. Besides user profiles capturing the literacy and expertise of a person, biometric sensors of smartwatches and fitness bands can be used to infer the physical state of the user by sensing, for example, heart rate or oxygen saturation. In stressful situations, visualization content could then be simplified in response. From a security perspective, fingerprint or facial detection can be required for unlocking the device, and thus, guarantee secure access to sensitive data.

Although the quality of these sensors will vary in fidelity and can sometimes only provide a rough indication, modern mobile devices can likely infer many of the dynamic factors discussed in this section, which leads us to a discussion of how to respond to them.

2.4 RESPONSIVE VISUALIZATION DESIGN STRATEGIES

Visualization designers have many strategies at their disposal with respect to responsiveness, and they often apply more than one strategy in combination in any given instance. In providing an overview of these strategies, due to the vast combinatorial space of specific applications, data types, and visual representation techniques, we cannot guarantee a completely exhaustive list of strategies. Furthermore, new mobile devices and sensing technologies may bring about new strategies in the years to come. As for now, our overview also relies heavily upon the work of visualization practitioners who have spoken or written about responsive design, as there is little research literature devoted to this subject, despite an interest in workshops [23, 60] and tutorials [12, 96] targeted at visualization researchers. Work by Hoffswell et al. [47] is a recent and notable exception, which described a system for responsive visualization design based on the documented practices of news graphics designers.

Our discussion largely remains agnostic to implementation, as language- or platform-specific guidance with regard to responsive visualization design is unlikely to remain current, whereas we can expect the strategies themselves to hold for a longer time. Nevertheless, we direct readers interested in web-centric implementation details to Hinderman [46] and Baur [12], who introduce techniques for CSS, HTML, and SVG, Möller [66], Bremer [18], and Körner [57] for D3.js, as well as O'Donovan [70] for React. Similarly, we do not offer substantial commentary on interactive environments and tools for responsive visualization design. For a perspective on responsive visualization design tooling in newsrooms, we refer to an example from Bloomberg News [79]. Existing visualization tools support responsive design to varying degrees, such as Tableau's configurable layout designer [24] or Datawrapper's options for responsive embedding [29]. From the research literature, Hoffswell et al.'s interactive responsive visualization design tool [47] provides a suite of features that could be incorporated into other visualization design environments, such as multiple concurrent previews of different device profiles, or the ability to customize the visualization design for a specific device without affecting the design choices for other devices.

The classes of strategies considered in this section (see Figure 2.1) include changes to the following: scale, aspect ratio, layout, level of detail, amount of data, annotation, attentional cues, animation, visual encoding, and interaction. Our discussion of these strategies complement and expand upon those that Hoffswell et al. [47] used to label a corpus of responsive news graphics, which included resizing, re-positioning, adding, modifying, and removing visualization elements such as axes, legends, marks, and labels. Many of the examples that correspond with these strategies are instances in which a desktop experience is converted to a mobile one, but we must stress that these strategies can also be applicable in the opposite direction, between different mobile devices, or between different states involving the same device, such as by changing contexts or by changing the orientation in which the device is held. Similarly, the motivation for applying adaptations within the examples is most commonly facing a reduced display space. However, all strategies could also be provoked by a changed information need of the user, for example, when selected aspects have to be communicated easily and quickly.

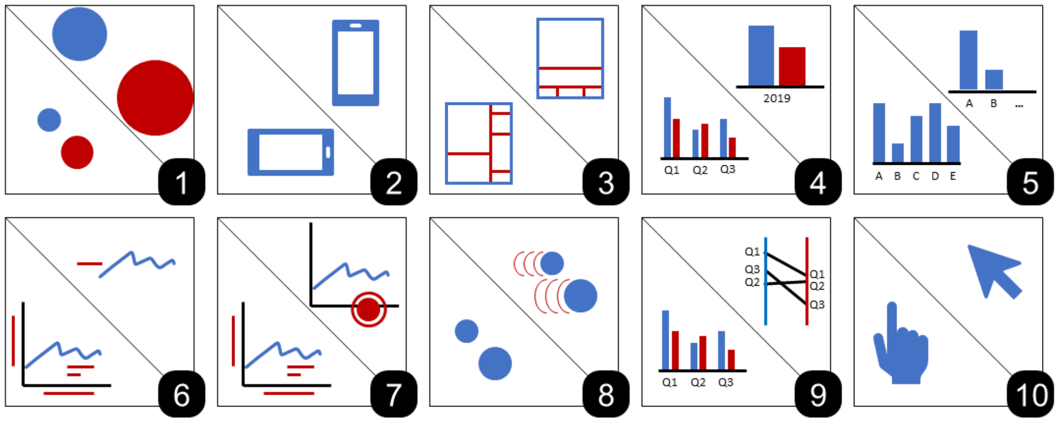
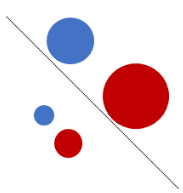


Figure 2.1: Responsive visualization design strategies considered in this chapter. Changes to: 1. scale; 2. aspect ratio; 3. layout; 4. level of detail; 5. amount of data; 6. annotation & guides; 7. attentional cues / dynamic guides; 8. animation / streaming data; 9. visual encoding; and 10. interaction

.

Of course, there is also the strategy of doing nothing: taking no responsive design action whatsoever or preventing viewing experiences from certain device profiles. Both approaches are bound to frustrate viewers [100], though the latter approach may be practical in the context of online research experiments, such as in Brehmer et al.'s mobile-only comparisons of time-oriented visualization techniques [16, 15], or Schwab et al.'s comparisons of panning and zooming techniques [81], where control over participants' viewing experience was essential to the experimental design. Finally, we preface our overview with a caveat that not all strategies may be available to the designer, as some will require specific types of devices [61] and/or specific forms of sensing, as summarized in the previous section.

2.4.1 Scale



The first strategy we consider is that of scaling content to fit within a physically smaller display. Despite their smaller size, contemporary mobile phones are equipped with high-resolution displays; consider the iPhone 12 Pro Max (released in Fall 2020) has a resolution of 2,778 by 1,284 pixels, resulting in more pixels per inch than the display of the latest 16-inch MacBook Pro released in 2019 (3,072 by 1,920 pixels). Given this high resolution, it is possible to scale visualization content initially intended for larger displays. However, this strategy breaks down if the visualization involves text, which will become illegible when scaled down [96], and thus one strategy is to apply different scaling functions to non-text content and text content [18], while another might involve abbreviating text labels in a systematic and consistent manner [83]. It is also ineffective to apply scaling if the visualization is to be interactive, particularly if interaction targets are individual marks or axes. Consider that as much as 92% of mobile phone usage is carried out while holding the device in portrait mode [74], so even a static visualization containing no text elements might be successfully scaled down for viewing in landscape mode. However, further scaling for portrait mode viewing may reduce its interpretability and it will make poor use of the full display height. As a consequence, scaling is a better strategy for visualization content that already has a tall aspect ratio [18].

Finally, we must consider that pure geometric scaling has been shown to incur a perceptual bias [97], and that leveraging an adaptive perception-based approach for resizing visualization might be warranted, as proposed by Wu et al. and realized in their ViSizer system [101] (see Figure 2.2). Other approaches exist that selectively scale text and image content from documents based on salience and uniqueness, which are also known as one instance of semantic zooming (see Woodruff et al. [99], Lam and Baudisch [58], or Teevan et al. [88]). However, these may not be appropriate for visualization content as they can fundamentally distort size and position encodings, except for visualizations that do not employ these encoding channels. Due to these drawbacks, scaling content is often combined with one or more of the other strategies described below, such as changing the layout or aspect ratio of content. If other strategies are unavailable, designers should at least allow viewers to zoom and pan the content, though they should realize that if sustained or repeated viewing is expected, this panning and zooming will quickly become tedious [96].

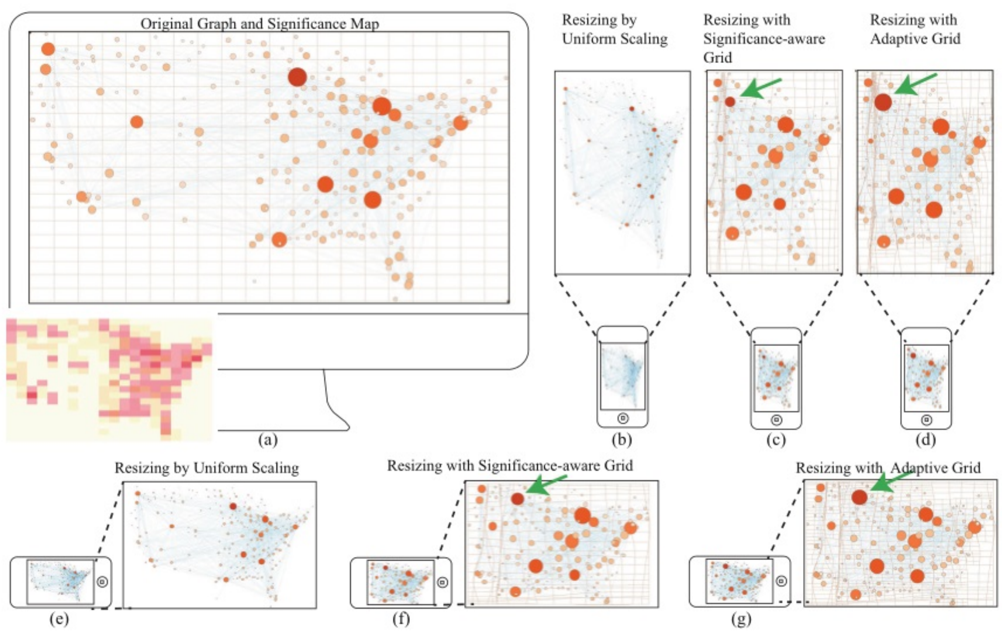
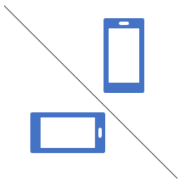


Figure 2.2: Wu et al.'s ViSizer system [101] scales visualization content according to either a significance-aware grid or an adaptive grid. The green arrows indicate where the two approaches produce different results. *Image © 2013 IEEE, reprinted, with permission from [101].*

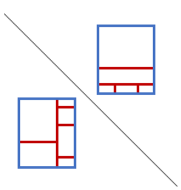
2.4.2 Aspect Ratio



Since most mobile phone usage is carried out while holding the device in portrait mode [74], it is prudent to make good use of this taller aspect ratio. As a result, one approach is to simply rotate content that was otherwise designed for viewing from a landscape PC monitor. However, text should remain un-rotated to ensure its legibility [12]. A simple example of this strategy is converting a vertical bar chart into a horizontal one [20]. Some designs are agnostic to changes in aspect ratio, as the absolute spatial position of marks is not meaningful, such as in circle-packing diagrams or force-directed node-link diagrams [18], where only the relative positions of marks to one another is meaningful. Some chart types are not amenable to mere rotation; for example, rotating a map reduces viewers' ability to recognize familiar geographic features, while rotating a scatterplot would violate conventions of reading direction, with higher values typically proceeding from left to right and from bottom to top. Line charts also resist rotation, due to the convention that the horizontal axis represents time proceeding from left to right.

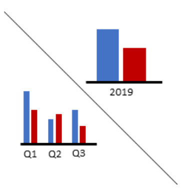
As an alternative to rotating content, it might therefore be tempting to fill the entire display height. This approach may be appropriate for some chart types but not others. For example, a map can simply show additional territory above and below the focal area, though as Hoffswell et al. [47] report from their interviews with news graphics designers, geographies such as the continental USA are more amenable to a landscape presentation. For line charts and chart types with continuous axes, such a change in aspect ratio can negatively affect perception [43, 87]. Of course, visualization designers need not to use the full display height; in many cases, a square aspect ratio is sufficient, and it is indeed the norm in mobile social media applications such as Instagram [7]. Finally, it should be noted that while the orientation of a device may impact the aspect ratio of a chart, this may not always be the case; consider that a change in orientation can alternatively result in an updated layout of content within a display without affecting the aspect ratio of individual content elements.

2.4.3 Layout



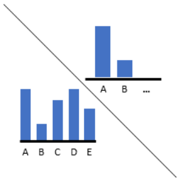
Until this point, our discussion has largely assumed a single piece of visualization content. This content seldom appears in isolation in practice; visualization may be accompanied by text, control panels, images, or additional visualization elements. We must therefore consider composite layouts consisting of multiple charts, documents consisting of interleaved and/or side-by-side text and visualization, and small multiple designs. Hoffswell et al. [47] refer to this as as re-positioning views, though we consider the broader scope of re-positioning visualization in relation to other content, such as text blocks that reference visualization. In the simplest case, a single row of content arranged horizontally for viewing from a desktop can be stacked vertically [12, 18]. However, consider the more typical case in which content can be seen as occupying a two-dimensional grid, such as in a small multiples design. It is the designer's responsibility to establish adaptive grid layout rules that anticipate different screen sizes and aspect ratios [12, 46]; perhaps a grid of six columns is ideal for a desktop display while a grid of two columns is ideal for a mobile display. As a consequence, content that is displayed simultaneously on a desktop display will cascade off-screen when viewing from a mobile display. Unfortunately, information can no longer be compared at a glance, and viewers' comparisons must rely upon memory. Furthermore, interactive brushing and linking across views is not as useful when the linked views are off-screen, unless there is some visual prompt that directs viewers to that off-screen content [10, 39] Despite this drawback, vertical scrolling is commonplace, fluid, and fast [26], and dashboard creation tools such as Tableau now provide layout guidance for mobile devices [24], in which the default mobile layout involves stacking content vertically. Scrolling a stacked series of charts interleaved with other content (such as text or images) is often preferable to alternative off-screen layouts, such as swiping or tapping page advance through a series of charts, as these interactions are less common than scrolling and may not be discoverable by viewers [41].

2.4.4 Level of Detail



Another strategy is to simplify and reduce the amount of detail in the visualization. This can be useful when the data are large or the screen space is limited as well as in response to human factors, such as different tasks or literacy being relevant in the current context. While Munzner [68] distinguishes several ways to manipulate the level of detail, we focus on a subset of approaches that we see as being particularly relevant to the topic of responsive visualization design. First, a designer could convert one chart into several charts by **faceting** on a dimension of the data, such as faceting a grouped bar chart into a series of bar charts, each displaying one of the group categories. This approach's disadvantage is that marks that were previously sharing axes can no longer be compared directly, and the newly introduced faceted views may not be simultaneously visible, necessitating scrolling or paging. If faceting is undesirable or unavailable, it may be possible to change the level of detail of a visualization via **aggregation**. This strategy is particularly evident in mobile maps, where aggregation is employed as a form of cartographic generalization [62, 96], such as aggregating counties into states and states into countries. **Reclassification** is a related concept, in which the number of categories or quantitative bins is reduced and consolidated, such as the reclassification of elevation levels in maps. Both aggregation and reclassification can be employed for other forms of visualization beyond maps. Examples of aggregation include a bar chart showing values per week which are then aggregated into bars per quarter, or clusters of adjacent points in a scatterplot that are aggregated and replaced with cluster points, or re-scaling quantitative attributes as ordinal ones. As for reclassification, examples include reducing the number of bins in a histogram, or consolidating categories in a color legend.

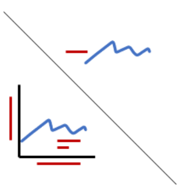
2.4.5 Amount of Data



To simplify visualizations incorporating many marks for a smaller display, designers can also remove marks in a systematic way via filtering and sampling. Hoffswell et al. [47] document more than two dozen examples of news graphics where marks are removed when converting a desktop graphic to a mobile one. The example they cite is one by which marks are removed from a symbol map about oil spills based upon a filter that sets a minimum threshold value on the size of the oil spill, and this threshold may vary depending on the size of the display. Another approach to reducing the amount of data is sampling based upon a statistical process. Whenever filtering or statistical sampling is employed, it is critical to inform the viewer that this has taken place as a responsive design measure, with some indication or ability to see what has been elided from view.

Yet another form of sampling is curatorial in nature and is appropriate only for communication-oriented visualization scenarios where there is a series of insights to be communicated to the viewer. In such cases, it could be that the entire visualization is visible from a desktop while a sampling of cropped areas of interest are visible from a mobile display. An example of this is a radial arc visualization by Sadowski [78], in which the entire interactive visualization is the desktop experience while a series of static zoomed-in regions of the arc diagram presented alongside descriptive text is the mobile experience.

2.4.6 Annotation & Guides



Charts, graphs, maps, and other forms of visualization present several types of visual elements to a viewer [54, 47], including at a minimum some data-bound marks and usually also some visual guides manifesting in the form of legends, axes, and grids. In communicative visualization scenarios such as in news graphics, there are also often several forms of annotation [75], such as additional text labels and attention-directing graphical cues such as arrows, color highlights, and shapes. Adjacent to a chart we might also find peripheral annotation such as titles, captions, source accreditation, and other footnotes. In their survey of responsive visualization design in news graphics, Hoffswell et al. [47] show that annotation and guides are often re-positioned, simplified, or removed altogether. Similarly, in a survey of visualization thumbnail links used in online news landing pages and in social media posts, Kim et al. [54] examined the differences between these thumbnails and visualizations appearing within the bodies of articles that they link to, finding that annotations and guides are removed and sometimes replaced with images.

These surveys are helpful in that they illustrate that there is no single order of precedence for re-positioning, simplifying, or removing annotation and guide elements; in some cases, a critical annotation for a single data mark may be more important to retain and emphasize than an axis, and thus the strategy of manipulating annotation and guides will vary greatly across instances. We also acknowledge that these existing surveys are biased toward communicative news graphics. In exploratory data analysis contexts, a systematic or rule-based approach to manipulating annotation and guides across devices may be warranted, such as in Andrews' demonstrations of responsive scatterplots, bar charts, and line charts [4, 5]. In an example of a responsive line chart (see Figure 2.3), Andrews and Smrdel [3, 5] show that as the display size decreases, axis labels first rotate and then are progressively removed at equal intervals, until they are removed altogether. Finally, axes and titles are removed altogether, leaving only a sparkline [93] with annotated endpoint values. Such bare representations are then also known as micro visualizations, word-scale visualizations, or glyphs, but have been shown to still be effective in communicating relevant data aspects [13, 38, 40].

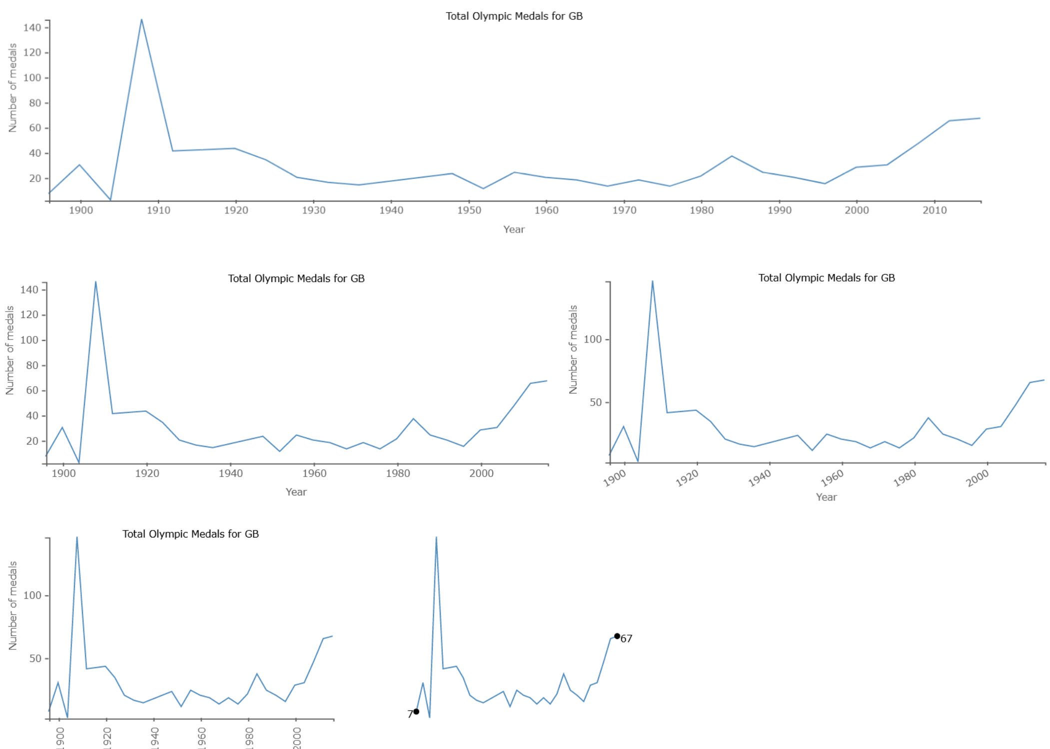
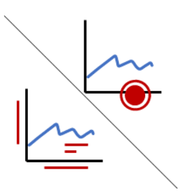


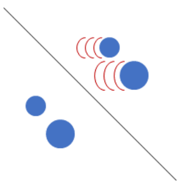
Figure 2.3: Screenshots of Andrews's responsive line chart example at five sizes [3]. With decreasing screen width, axis ticks and labels are gradually reduced, rotated, or removed completely. Screenshots used with permission.

2.4.7 Attentional Cues / Dynamic Guides



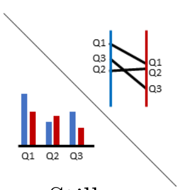
In contrast to the approach of modifying or removing annotation and guides, there is also the strategy of adding annotation, guides, and other cues to a visualization to support viewing from a small-screen device. For instance, while it may be feasible in desktop viewing experiences to display a large and detailed chart in its entirety, a mobile experience might augment a cropped, zoomed-in version of the chart with a minimap view of the entire chart [22]: a form of focus + context or overview + detail. An alternative to the minimap approach is to add graphical annotations that indicate the distance to and relative orientation of areas of interest that are currently off-screen [10, 39]. Moreover, labels can play an important role for understanding the visualized information. Fuchs et al. [37] present dedicated algorithms for labeling technical drawings on mobile devices. Similar approaches could also be applied to label for example node-link diagrams in mobile viewing contexts.

2.4.8 Animation / Streaming Data



As with the removal vs. the addition of annotation and guides, we are similarly aware of cases where an animated design for desktop viewing becomes static when viewed from a mobile device, as well as cases in which the opposite occurs. An animated visualization of continuously streaming data may require more processing power than what a mobile device could provide, or a full set of animation controls may take up too much space in a mobile display, and thus a series of static snapshots or a looped animated "Data GIF" [42, 86, 84] may be a suitable compromise in a mobile viewing context. There are also cases in which a static small multiple design intended for desktop viewing becomes a looped Data GIF for mobile viewing. This is advocated by the NPR news graphics team [14], for example, in their article about the growth of Wal-Mart stores in suburban areas [69]. Despite the apparent appeal of Data GIFs in such instances, there is evidence to suggest that static small multiples in mobile visualization design can elicit comparably accurate perceptual judgments [15]. Ultimately, animation can be engaging and memorable, particularly in a communicative news graphics context; however, it can also be distracting and disorienting, so designers should exercise caution. It is entirely possible to craft effective combinations of visualization and animation in both desktop and mobile viewing contexts, as evidenced by the apparent popularity of content incorporating responsive "scrollytelling" [41].

2.4.9 Visual Encoding



Until this point, each of the strategies we have mentioned assumes little, if any, change to the visual encoding. However, this potentially drastic strategy of changing the fundamental design is sometimes warranted, though as Hoffswell et al. [47] show, it is not a popular approach, at least in news graphics design.

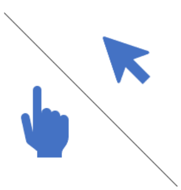
Still, an early approach to adapting the visual encoding to display properties has been proposed by Radloff et al. [73]. They use a primary mapping that is consistent across devices and a redundant secondary mapping that varies depending on the device. They successfully tested their approach with a scatter plot being used on a large, regular, and small display.

Bremer [18] cites an example from her own project portfolio, in which a radial paired dot plot is converted into a slope chart. Camoes [20] gives us several additional examples of how a bar chart might be better presented as a strip plot, how a paired bar chart could be transformed into a slope chart, or how a population pyramid could be transformed into a set of overlaid population curves. In each case, the latter is optimized for mobile displays without resorting to sampling or filtering the data. These examples should prompt designers to pause and consider whether a particular encoding design choice for mobile viewing is a better one to use across all viewing platforms, and that a mobile-first design approach may lead designers to more responsive designs relative to a desktop-first approach.

In addition to the mentioned approaches that select and replace a visualization technique as responsiveness measure, dynamic and smooth adaptation methods like *semantic zooming* can be used. Another form of semantic zooming (selective scaling) was already mentioned as a possible tactic in the section on *Scale* earlier. In the context of *Visual Encoding*, a different flavor might be applied: Depending on the available display space or zoom level, the visual encoding can be changed smoothly. For a time series representation, the visualization could smoothly morph [77] from a line plot to a horizon chart [44] when the height of the graph falls below a certain threshold. Such mechanisms can also be used within local zoom areas in focus+context techniques. For example, cells in a matrix visualization can be scaled up to embed charts revealing details about the underlying data [49]. Interestingly, the embedded charts themselves can behave responsively by adapting to the available display space.

Finally, let us revisit the easy choice to disallow mobile viewing, which we know to be frustrating for viewers. An alternative would be to replace a visual encoding with a simple table of the data, or at least a tabular summary [96]. For example, while a node-link representation of a network may be appropriate for larger displays, a sorted tabular representation of nodes may be more appropriate for mobile displays [33].

2.4.10 Interaction



Last but not least, we address the topic of responsive interaction design for visualization. As interaction with visualization on mobile devices is the subject of the next chapter, a thorough discussion of techniques will not be examined here, nor will we attempt a mapping of desktop to mobile interaction techniques. Instead, we offer some high-level comments with respect to responsive interaction design for visualization.

First, there is the question of whether interaction is necessary. This question is perhaps more relevant in the context of communicative news graphics, as newsrooms such as *The New York Times* have reported how rare it is for viewers to interact with these graphics [1], leading their deputy graphics director Archie Tse to declare that the often best visual storytelling is static [92]. While interaction remains to be a topic of debate within the visualization practitioner community [2, 11], entirely scroll-based interaction remains to be a popular design choice across devices [41]. For another example, tooltips that reveal themselves upon hover interaction will be inaccessible to mobile viewers, so fixed tooltips or tap-to-reveal tooltips may be preferable for those viewing from a mobile device [12]. Similarly, a slider below a chart provides another way of revealing additional guides, annotations, or details-on-demand [27].

In non-communicative or exploratory visualization contexts, interaction is often essential to the analytical process [91], and thus it is necessary to rely upon discoverable interactions that allow for similar levels of exploratory behavior across platforms. Scrolling, panning, and zooming work well across platforms, data types, and visual encodings, and initial zoom and pan positions can provide cues that such interaction is possible [18]. The selection of individual marks (e.g., dots in a scatter plot) can prove difficult though due to the smaller screen and depending on the input modality. One approach to tackle this is increasing the interactive area of a mark by a few pixels beyond its graphical representation [82, 25, 98]. Yet, for dense visualizations this approach might not be sufficient. In such cases, an invisible Voronoi tessellation can be used to define the interactive areas [19].

This concludes our discussion of possible strategies for responsive mobile visualization. Next, we shed some light on open challenges and research opportunities.

2.5 CHALLENGES & OPPORTUNITIES

Responsive design is crucial to the success of visualization on mobile devices. While we have pointed to strategies and examples of responsive design applied to visualization that may benefit practitioners and researchers alike, it is also our intent to inspire future research. In this section, we revisit the major challenges and opportunities pertaining to responsive visualization design that should be tackled in future research.

2.5.1 Develop Once, Deploy to Many

Many projects incorporating visualization are tailored to a particular class of device. Developing multiple versions of a visualization project for different devices is expensive [79], particularly if it involves interactivity [92]. In practice, this repeated effort and cost either limits the deployment across devices or results in a drastic simplification of the visualization design, such as by removing interactivity altogether. A responsive design mindset from the outset of a project can facilitate a *develop-once, deploy-to-many* process, which can keep development costs down. However, such a mindset is seldom part of a visualization designer's training. Existing visualization design models such as the nested model [67], the visualization design triangle [65], or the five design sheets method [76] do not explicitly consider the aspect of responsiveness. Responsiveness must become an integral part of visualization design pedagogy so that novice visualization designers learn to approach responsiveness in a systematic way. This requires a rethinking of not only basic charts in isolation, but also the combination of multiple representations in more complex visualization applications. Being responsive is more than fixing visualizations for mobile use [100]. It involves thinking about adaptations at all stages of the visualization design, from requirement elicitation to summative evaluation.

2.5.2 Guidelines for Responsive Visualization

While a responsive mobile visualization mindset can reduce the need for redundant parallel development effort across devices, we acknowledge that the design space for responsive visualization is substantial. We further contend that a foundation of responsive web design is helpful but not sufficient for responsive visualization design. As we showed in the previous section, a visual representation can be adapted in various ways to account for different aspect ratios or display sizes, not to mention different usage scenarios. In responsive web design, grids are often used as a guiding principle. However, for visual representations of data, grids alone might not be sufficient. Unfortunately, the visualization research literature thus far does not provide any substantial guidance beyond responsive web design. While Wu et al. [100] provide a good overview of the most common issues when displaying visualizations on mobiles, we still lack support for avoiding these issues when designing a responsive visualization in the first place. Future research should investigate and expand upon the strategies and practices described in the literature and propose a set of evidence-based guidelines.

2.5.3 Evaluating Responsiveness

The process of evaluating visualization is challenging and can assume many forms [59]. While evaluating visualization on mobile devices is discussed at length in Chapter 6, we take this opportunity to comment briefly on the evaluation of responsiveness in particular. Evaluation of responsive visualization design does not necessarily require large human factors studies. Instead, it seems to be viable to evaluate responsiveness using a set of evidence-based heuristics and guidelines. It may also be possible to quantify differences in the amount of information conveyed in different manifestations of visualization design across devices. Given a possible quantification, automated tests for detecting information loss from larger to smaller devices may be feasible. Finally, one could imagine an evaluation protocol that draws from Kindlmann and Scheidegger's algebraic process for visualization design [55], in which given a set of competing responsive visualization design strategies, the effects of small variations in a dataset could be quantified across different devices profiles for each strategy. This process would culminate in an identification of a strategy that results in a balance between legibility and discrepancy across devices.

2.5.4 Authoring Support

Embodying responsive visualization design guidelines or heuristics in authoring tools is another possible direction for researchers and tool builders. Many web design tools assist developers with templates and device emulators, allowing them to quickly generate prototypes and refine them interactively. While some visualization design environments and languages offer prescriptive guidance (such as the Vega Lite editor [80]), many existing visualization tools do not provide dedicated support for responsiveness. Tableau provides a mobile layout designer and automatic layout for dashboards [52], though other strategies beyond layout manipulation are not offered within this environment. Going forward, researchers and tool builders should identify ways of surfacing other strategies and aspects of responsiveness and into visualization languages and interactive authoring tools. Hoffswell et al.'s recent prototype tool [47] for responsive visualization design is a promising step in this direction (see Figure 2.4), incorporating several of the strategies that we summarized above.

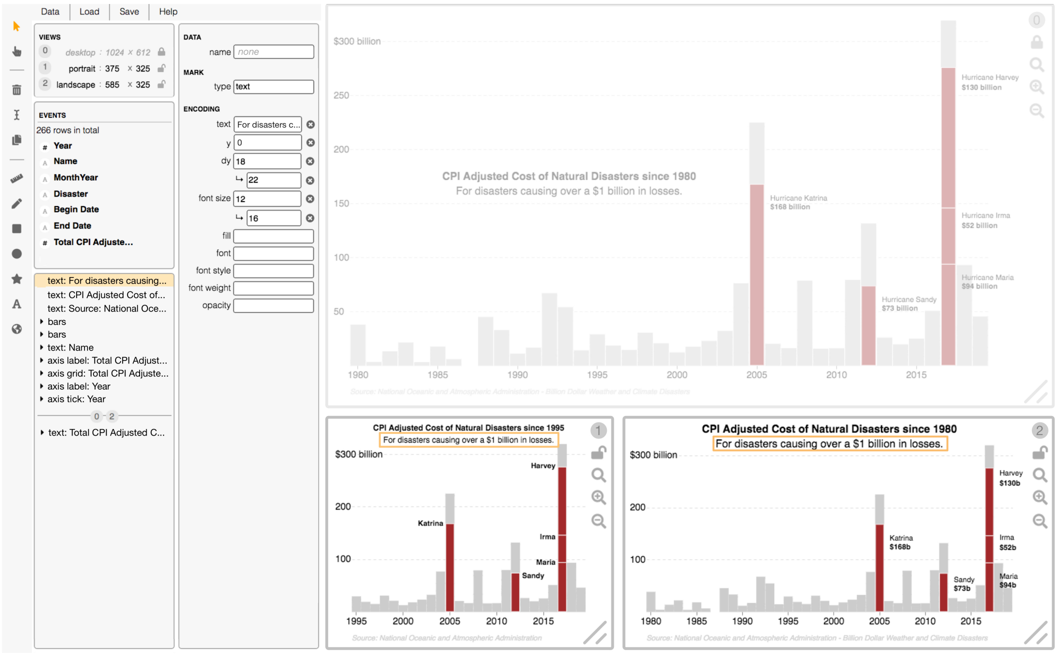


Figure 2.4: Hoffswell et al.'s recent prototype tool [47] for responsive visualization design allows one to preview multiple chart sizes simultaneously. *Image © 2021 Jane Hoffswell, used with permission.*

2.5.5 Responsiveness for New Devices

Achieving responsive visualization design on tablets, phones, and watches is already feasible, though often laborious, and it has become a core concern of visualization design. Yet, emerging and future display technologies will challenge existing approaches to responsiveness. New devices will have properties and characteristics that enable new types of changes that responsive visualization design must take into account. For example, we do not yet have a good understanding of how responsive visualization design could manifest with flexible bendable displays (such as the Samsung Galaxy Fold), not to mention shape-changing displays, which can transform in ways not yet examined in the research literature. Furthermore, upcoming mixed reality technologies might require a special kind of responsiveness, as display constraints no longer exist in the same sense, while the interplay with the real world will put up new ones. The prospect of such devices will be discussed in greater detail later in Chapter 9 of this book. For now we can conclude that identifying responsive visualization strategies for new devices is an exciting direction for future research.

2.5.6 Cross-device Responsiveness

Promoting responsiveness as an integral part of the design process will not only enhance mobile visualization; it will also facilitate multi-device visualization, where multiple heterogeneous displays (large and small, stationary and mobile) are operated in concert to see and interact with representations of data. In multi-device settings, visual representations (or parts of them) can be moved seamlessly from one device to another [72]. For example, if a smartphone is too small to make details sufficiently visible, a throw gesture could transfer the visualization onto a larger device [28]. Responsive visualization design is integral to the impression of seamless continuous interaction across devices. While we have recently seen research dedicated to ensuring responsive visualization design in multi-device environments [9, 50], more research could build upon this work and examine how multi-device responsive visualization design might generalize across contexts and data types.

2.5.7 From Technical to Contextual Responsiveness

Responsiveness as discussed thus far is contingent upon device capabilities and states, such as the size and aspect ratio of the display or the device orientation. In addition to these technical aspects, there are contextual aspects as well, though these are seldom considered in responsive visualization design. Visualization designers and researchers should continue to investigate how mobile visualizations could respond to changing human factors and changing environments. For instance, some wayfinding, music, and podcasting apps infer that the device is in a moving vehicle and offer a simplified driving mode interface not to distract the driver. However, more can be done to infer these changes of state. For instance, wearable devices such as watches could infer a person's mental and physical state. While current technology enables us to determine whether a person is stressed, determining whether they are in flow or immersed in an application remains challenging. Gaze detection via front-facing phone cameras might be useful in this regard [53]. For any given application, designers should determine the possible states that people could be in and what the typical state transitions might be, and design suitable responsive transitions for these state changes.

2.5.8 Make Responses Understandable

Finally, visualization designers should strive to make responsiveness transparent and understandable to the user. Because responsiveness is a form of automatism, the rationale and effect should be predictable and reproducible. For instance, one should be able to determine why a visualization responded to a change in the way it did, as well as be able to understand how a new visual representation is related to a previous representation. The latter aspect could be addressed by smoothly animating visual representations that changed due to responsiveness. The former aspect, that of making the rationale behind responsiveness transparent, requires additional effort. In current manifestations of responsive visualization design, responsiveness is hard-wired into the system. Making it explicit would allow designers to explain the inner workings to the user on demand. Finally, allowing for the responsiveness to be configurable would allow users to tune it to their preferences.

2.6 SUMMARY

While responsive web design is an established practice, responsive mobile visualization design has received comparatively little attention to date. With this chapter, we shed some light on this topic by looking at factors that impact visualization usage as well as possible design strategies. In conclusion, we reemphasize that responsive visualization design involves challenges beyond those encountered in web design: First, visualization content is more sensitive to changes in size, aspect ratio, and interaction modalities, so this content cannot be simply scaled down to fit the screen width. Second, this sensitivity also means that it is not enough to consider the display-related factors in isolation (as is typical in responsive web design), but also the usage context and the environment where the viewer is located. As a consequence, designers require additional context-aware strategies to provide effective visualization. While practitioners have provided an initial set of strategies with respect to how to design responsive visualization, the visualization research community should continue to investigate novel ways to address the challenges of responsiveness on mobile devices and beyond.

ACKNOWLEDGEMENTS

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