WHERE DO WE GO FROM HERE?
UNDERSTANDING MOBILE MAP DESIGN

By

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ABSTRACT

As global smartphone ownership rises, so does the global usage of mobile maps on smartphones. As mobile map usage increases, it is essential to understand what separates mobile maps as a unique from of cartographic expression. This research answers two questions: how do smartphones enable and constrain mobile maps as a physical mapping platform, and how are mobile maps currently being designed in the context of these constraints and enablements. I conducted two content analyses to answer these questions. First, I used the website GSMArena to determine how smartphone design has evolved over time using a series of codes related to the sampled information. Constraining factors included the bandwidth, battery life, processing power, and the screen design of the device. Enabling factors encompassed included sensors, GPS and the location awareness of smartphones, and unique interactivity potentials. Second, I selected a sample of mobile maps and evaluated them on the traditional interactive cartography axes of data, representation, and interaction. Data characteristics of the sample investigated included data types, sensor data, non-spatial data, and data conversation options. Representation in mobile maps was considered as a function of how map features were represented, basemap design, potential map views, and the inclusion of map elements. Interactivity was broken down into the components of work interaction operators, enabling interaction operators, and unique interactivity potentials. This research concludes by synthesizing the results of these two content analyses to provide mobile map designers a series of recommendations for improving their utilization of smartphones as a mapping medium.

CHAPTER 1: INTRODUCTION TO MOBILE MAPS

1.1 Purpose and Significance: Mobile Maps and Society

In this research, I seek to improve the design of mobile maps by reviewing the constraints and enablements of the mobile medium and the subsequent influence on the data, representation, and interaction design of popular mobile maps. Mobile mapping technology is growing in popularity globally. By the summer of 2019, 81% of U.S. residents reported owning a smartphone capable of supporting sophisticated mobile mapping applications, an increase from just 35% market penetration only eight years earlier (Anderson 2019). This mirrors smartphone ownership for other advanced economies, where on average 76% of adults in 2019 reported owning a smartphone. However, despite an uptick of smartphone ownership in developed and emerging economies, the digital divide remains: only 45% of adults in emerging economies report owning a smartphone (Taylor and Silver 2019).

In the following, a ***mobile map*** describes "a cartographic representation or mapping application explicitly designed for viewing and interaction on a digital, handheld, and moving computing device" (Ricker and Roth 2018: online). Widespread smartphone ownership means that users are now commonly embedded in the environment depicted in their mobile maps. Of current smartphone owners, as many as 95% utilize location-based services on their smartphones for obtaining directions, recommendations, and other mappable information specific to their location (Anderson 2016). As a result, location-aware mobile mapping has become one of the most used and most profitable capabilities of the smartphone (Dao, Rizos, and Wang 2002). A mobile map serves as an interactive information repository while moving through the landscape as opposed to a fixed abstraction of the landscape

(Gartner, Bennett, and Morita 2007). Pervasive mobile map usage therefore marks a distinct departure from prior reliance on static maps, and possibly signals a fundamental shift in the relationship between cartography and geography as the two disciplines collide at the site of the mobile device (Roth et al. 2018). Understanding this changing relationship between maps and place becomes increasingly important as long-held assumptions of how environments are remembered and navigated (e.g., Lynch 1960) are complicated by mobile mapping technology.

Several scholars are beginning to explore the unintended consequences of mobile mapping from a geographic perspective: assessing if it impedes our spatial cognition (e.g., Ishikawa et al. 2008; Dillemuth 2009; Montello 2009), voicing concerns about our dissolving locational privacy (e.g., Dodge and Kitchin 2007; Wilson 2012), and questioning how mobile computing technologies are altering the social fabric and spatial scales of user interaction with the landscape (e.g., Elwood 2010). Still, research on mobile mapping is in its infancy, and our understanding of the broader impact of mobile maps on our experience of place and use of geographic information remains limited (Ricker, Schuurman, and Kessler 2014). As smartphones increasingly mediate our experiences, we must learn how our mobile map design choices influence this experience of place and transformations therein (Davidson 2014). Until we understand how mobile mapping influences our geographic understanding, the technology (and multinational corporations developing the technology) will dictate what people do, rather than people shaping the technology to meet their needs.

The ways in which mobile devices—specifically smartphones—have changed over the last decade further complicate these questions. ***Smartphones*** are mobile telecommunication devices which, in addition to their ability to make phone calls, come equipped with a wide array of additional sensors that enable constant data connectivity, location awareness, and unique interaction possibilities. Smartphones have rapidly expanded in their network connectivity and bandwidth speeds, their battery life, their screen size and pixel density, their processing power and speed, and their GPS accuracy and increased the number of other sensors packaged within the smartphone since their introduction. Accordingly, it is necessary to examine how the smartphone as a mobile computing medium has changed through time and to understand how its evolution has influenced the data included in mobile maps, the way data is represented in these maps, and how the user is able to interact with mobile maps on a smartphone. Together, by understanding both the hardware and the software components of the mobile mapping system, it becomes possible to understand how to improve the development and design of these maps for users going forward.

1.2 Foundational Concepts for Mobile Cartography

Mobile maps are a unique case for cartography. Arguably, mobile is a new medium for maps, defined by the digital computing constraints imposed by the physical hardware of the smartphone. Mobile hardware concerns can include rendering and interaction limitations imposed by reduced processing power, information complexity issues imposed by the size of the screen and various viewing conditions, and interruptions in the user experience imposed by non-wired network (Qi and Gani 2012). Accordingly, the design and use of maps on smartphones is fundamentally different from maps made for the more-established cartographic mediums of print and web, requiring different design solutions for mapping applications. Because of this nascent hardware technology, and limited time-tested software conventions, mobile maps overall are not as well understood by researchers as static maps or interactive maps intended exclusively for desktop computing (see Meng, Zipf, and Reichenbacher 2005; Muehlenhaus 2013, for existing treatments of mobile map design).

Mobile hardware technology has been steadily evolving since the introduction of smartphones and characterizing the historical and current medium for which mobile maps have been designed and developed is key to understanding the potential of these technologies for cartography. Smartphone hardware places extreme demands on both cartographic and geographic information systems brought on by the unique limitations of mobile computing (i.e., constraints), while also expanding their potential through the inclusion of GPS and other sensors, the expansion of location-based services, and ease of mobility (i.e., enablements).

Although many of the constraints inherent to smartphones have been mitigated in recent years by advances in mobile hardware technologies, they represent deeper considerations for cartographic theory as mobile emerges as a new cartographic medium. Further, even as new devices are introduced, mobile technologies remain expensive and are not universally available, reifying a mobile digital divide. Mobile map designers therefore must compromise and design for the lowest common denominator or make choices about the technologies, and therefore the communities, they will (and will not) support. Tracking and characterizing the history of mobile mapping technology is therefore important for understanding and overcoming the digital divide. Edwardes et al. (2005) describes the key hardware constraints to mobile mapping to be small and low resolution screens, limited processing power, and intermittent network connections. As mobile devices have given way to the ubiquitous smartphone, these constraints have expanded to include the limitations on battery size, flexible screen orientation, divided attention with the real world, and highly variable viewing conditions (Roth and Ricker 2018).

Although the mobile medium imposes several constraints on mobile map design, it also presents new design opportunities through unique enablements that set mobile apart from other media. Modalities for interacting with mobile devices are fundamentally different from traditional paper maps or desktop computing in how users can interact with the device, the mobility of the device, and their utilization of GPS and the subsequent provision of location-based services through the device. These enablements stem from the wide array of sensors that come standard with smartphones, and the typically small size of the device that makes it easy to carry at all times, creating the potential to seamlessly integrate the mobile map into all facets of life (Roth and Ricker 2018).

As the experience of cartographic interaction becomes augmented and challenged through its adaptation to mobile, cartographic design principles also are being challenged. Interactive cartographic design workflows can be distilled into the three facets of data, representation, and interaction design. (Donohue 2014; Tolochko 2016). This three-part design workflow applies to both the creation of mobile maps as well as the evaluation of the mobile medium. The second component of this research explores what kinds of data is being included in the sampled mobile maps, how this data is being represented in mobile maps, and how the users are able to interact with these representations through the smartphone.

To understand how the design of mobile maps is different, I began by recording the data characteristics of the sampled mobile maps. This included what GIS data was featured in the mobile map, what sensor data was utilized, if non-spatial data also was used, and if users were provided with the option to conserve data within the mobile map. To categorize how data is represented in the map, I then recorded representation solutions for common map features, basemap characteristics, map views, and map elements in the sampled mobile maps. Finally, I recorded how users can interact with these representations in the mobile maps, including what interactions could be performed to complete a task, enabling operators, and if there were any opportunities for unique interactivity and feedback within the mobile map.

1.3 Problem Statement and Research Questions

For this project, I draw from tenets of cartography to understand how data, representation, and interaction design conventions are translated and challenged when adapted for the constraints and enablements of smartphones. Specifically, I employ emerging concepts from interactive cartography to deconstruct the contemporary landscape of mobile mapping technology and to articulate the design space for mobile maps. Further, I add nuance to the discussion of cartographic design by identifying gaps in current map design potentialities and suggest design guidelines for maps created for smartphones.

Accordingly, my research addresses three questions with constituent objectives:

RQ 1: What makes smartphones a unique medium for map design and development?
- **RQ 1a:** What are the constraints imposed by the hardware of the mobile medium on cartographic design?
- **RQ 1b:** In what ways is cartographic design enabled by the hardware of the mobile medium?

RQ 2: What are the emerging best practices for mobile map design and development?
- **RQ 2a:** What information is included in the mobile map?
- **RQ 2b:** How is this information represented in the mobile map?
- **RQ 2c:** How are users able to interact with these mobile map representations?

I investigated these questions through a two-stage process using a quantitative content analysis of secondary sources (e.g., Suchan and Brewer 2000; Muehlenhaus 2011). I address RQ1 in Chapter 2 through a comparative technology analysis of popular smartphones released between 2007 and 2017. Specifically, I collected the technical specifications of 224 smartphones to identify patterns, trends, and anomalies in mobile hardware to characterize mobile versus other media used in cartographic design. This survey is framed by eight constraints and enablements of the mobile medium and examines their potential influence on map design. These constraints and enablements are bandwidth, battery life, mobile screen displays, screen viewing conditions, processing speed, unique interactivity, mobility, and GPS.

I address RQ2 in Chapter 3 by applying visual content analysis to popular mobile map applications as available in Summer 2019. Specifically, I collected 36 apps based on their download metrics and deconstructed their design according to dimensions of data, representation, and interaction. Together, these two content analyses provide insight into the current state of mobile map design and provide a basis for recommendations on how to conceptualize mobile map design and development as smartphone technology continues to evolve.

In Chapter 4, I summarize key findings related to research questions and provide suggestions for further research and best mobile map design practices. This work sets a baseline of understanding for what information is being presented through mobile mapping platforms and makes recommendations for how to better utilize these platforms.

CHAPTER 2: QUANTITATIVE CONTENT ANALYSIS OF MOBILE HARDWARE TECHNOLOGY

2.1 Method: QCA of Smartphone Hardware Constraints and Enablements

In his chapter, I set out to understand what makes smartphones a unique mobile mapping medium. I explore the constraints of the smartphone including bandwidth and the role that network generations have on overall data access speed, device battery life and how this is impacted under different conditions, screens and the role screen technology has on visibility, and the limitations and developments of processing power over time. I also investigate what makes smartphones unique as mapping platforms through the unique interactivity they facilitate, their mobility, and the inclusion of GPS and other sensors within the smartphone.

2.1.1 Overview

I used content analysis to understand how smartphone technology has evolved over time, which in turn serves as a foundation for assessing constraints and enablements on mobile map design. By focusing on the technical hardware specifications of different smartphone models, it is possible to begin to differentiate between design choices intentionally made by the map designer independent of the mobile medium and isolate the design decisions that are the product of the map being created specifically for use on mobile phones.

Quantitative content analysis (QCA) describes the systematic analysis of a collection of documents to identify and characterize patterns from within the documents (Rose 2016). This project employs QCA to interpret both the visual elements of mobile maps as well as the technical elements behind design. QCA as a means of evaluating an interactive map is an example of a theory-based method of examining secondary sources, in this case individual mobile phones, to understand the application domain holistically (Muehlenhaus 2011; Kessler and Slocum 2011). One specific form of content analysis used in interactive cartography and visualization is the *competitive analysis*. Competitive analyses in cartography often do not take into account the influence of device hardware on design, and in this work I seek to fill this gap in cartography by revealing best practices and unmet opportunities in mobile map technology and design as they relate to physical smartphone design.

2.1.2 Materials

To gain a deeper understanding of how mobile phones have evolved over time, I conducted a survey of flagship smartphones in February 2018. Beginning with phones released in 2007 to mark the sale of the first Apple iPhone, I gathered the top five mobile phone manufacturers from 2007−2017 (eleven total years) based on Gartner press releases (e.g., Gartner 2008). I then used the website GSMArena to compile a comparable dataset of smartphone specifications. I selected GSMArena over alternatives (e.g., PhoneArena, PhoneScoop) to take advantage of their long history of phone reviews, the quantity of sampled phones available on the site, their international focus, and the consistency of the specifications collected by the site over time. These factors promoted consistency within the sample and allowed for temporal comparisons of smartphone specifications that would have been otherwise impossible.

2.1.3 Procedure

I conducted the analysis through a systematic sampling process where, after identifying the top five mobile phone manufactures in a given year, I used the “Phone Finder” feature on GSMArena to select phones released by each identified manufacturer within the year for either the iOS or Android operating system. In 2017, the most popular operating system in the world was Android, with 86.6% of smartphones sold in Q1 sold with Android installed. iOS accounted for 13.7% of market share the same quarter, with competing operating systems accounting for just 0.2% of the market (Gartner 2017). Accordingly, I limited the smartphones to these two operating systems to ensure continuity and comparability over time in the sample. iOS was released to support the first iPhone in 2007, and Android followed one year later with the release of the first android smartphone (T-Mobile G1) in 2008.

I then ordered the resulting selection by popularity and captured the top five unique most popular phones for inclusion in the sample. I selected the United States version for the sample in cases where mobile phone manufacturers released region specific versions of top phones that all ranked within the top five for the year. In all, I collected 224 phones for the sample from a total population of 3,716 Android or iOS phones reviewed on GSMArena between 2007 and 2017.

I then coded the specifications for each smartphone according to the constraints and enablements introduced in Chapter 1, using the individual phone pages on GSMArena. I scraped this information with a node.js script that iteratively read the individual pages for each smartphone specified as part of the sample and wrote the contents of each page to a single spreadsheet for comparison and analysis. The results of the sampling collection and specification coding process can be downloaded at https://github.com/LeanneAbraham/thesis/blob/master/specs-analysis/output.csv.

2.1.4 Analysis

Finally, I analyzed the coding results to understand how individual specifications of the sampled phones evolved over time and how these changes might impact the experience of using a mobile map. Specifically, I organize the collected specifications according to the constraints and enablements of mobile map technology as outlined by Roth and Ricker (2018), providing some discussion and interpretation on how these constraints and enablements impact mobile map design. I explore the results of this analysis in the subsequent subsections.

2.2 Constraints

The smartphone as a physical computing device constrains mobile maps through the limiting of bandwidth, battery life, the design of the screen, the physical conditions the device is used in, and the amount of processing power available to the user. An overview of these constraints is provided in Table 2.1. The following section explores the influence of these constraints on mobile maps as well as how the design of smartphones has changed over time. I aim to provide insight into both how mobile map designers might better understand the influence of the physical hardware of the design of mobile maps to design smarter maps.

Table 2.1: An overview of mobile mapping constraints related to the physical design of smartphones.

Constraint	Code	Definition
Bandwidth	*Network Generation*	The technology that mediates the speed at which data access is possible
	Network Speed	The speed users can download or upload data over a mobile network. Dependent on the mobile network generation.
Battery Life	*Battery Capacity*	The amount of energy, measured in milliampere hours (mAh), stored in the phone battery.
	Battery Endurance	The length a smartphone battery lasts after the user makes 1 hours of 3G calls, watches 1 hour of videos, and browses the web for 1 hour.
	Battery Replacement	The ability to remove a device battery and insert a new battery without specialized tools
Screens	*Screen Size*	The total area of the screen
	Screen Resolution	The number of pixels available per square inch of screen.
	Screen-to-Body Ratio	The ratio of screen to body on the face of the smartphone
	Screen Aspect Ratio	The height of the screen divided by the width
Screen Viewing Conditions	*Screen Type*	The type of display used in the smartphone
	Indoor Contrast Ratio	The greatest ratio in luminance of white to black the smartphone can produce
	Outdoor Contrast Ratio	The greatest ratio in luminance of white to black the smartphone can produce in bright sunlight
Processing Power	*Processors*	Embedded chips that enable the smartphone to perform operations on external data sources.

2.2.1 Constraint: Bandwidth

One of the most powerful enablement's of mobile phones is their regular connectivity to a data source. Connectivity constrains traditional cartographic design in several ways: for example, it is recommended that mobile maps limit the data volume when loading or interacting to the degree possible so that the map loads faster, resulting in a more seamless user experience and a lower impact on costly data plans. Such data conservation is completed through using vector tiles over raster, caching essential information, and generalizing represented data as much as possible (Muehlenhaus 2013; Buttenfield 2002; Meng et al. 2005; Ricker and Roth 2018). I collected two specification codes related to networks: network generation and network speed.

Network Generation

Network generation describes both the bandwidth and the technology used by the smartphone, broadly referring to the speed at which data transfer is possible (Adachi 2001). Network speed refers to downlink and uplink rates that the smartphone is capable of achieving, as determined by the network connected to the device (Huang et al. 2012). These networks can be broken down into 1G, 2G, 3G, and 4G.

1G refers to the first generation of analog mobile communication systems that were deployed around 1980 with a data transfer rate of around 2.4 kbps (kilobits per second), followed by ***2G*** networks with a transfer rate of ~64kbps. The increase in data transfer speeds marks an evolution from networks intended for voice services to networks intended for multimedia communication. ***3G*** networks, which had data transfer rates of up to 2mbps, were developed out of a need for better multimedia handling, higher capacity for data transfer, and to begin working towards a global standard. ***4G*** networks are the current standard, with data transfer rates exceeding 1gbps under ideal circumstances. Data transfer rates are highly variable and depend on how quickly the smartphone is moving, if it is inside a building, and how close it is to a network node. Best data transfer rates are achieved by stationary outdoor devices near a network node (Adachi 2001).

Accordingly, the network generation code ranges from 1G, or the analog communications standard (the only non-digital network), through the soon-to-launch 5G that promises to allow for data transfer speeds of over a gigabyte per second (Agar 2013). None of the sampled phones used 1G or 5G, with phones instead within generations from 2G through 4G. The original iPhone (Fig 2.1A) launched with 2G data capabilities, but since its release all other mobile phones sampled were equipped with the potential to tap in 3G networks (223/224; 99%), and later, 4G networks (125/224; 56%). In 2017, all phones sampled supported both 3G and 4G networks.

Network Speed

As Figure 2.1 illustrates, of the sampled smartphones from 2007−2017, the most common 3G network technology was HSPA (High Speed Packet Access) with 213 of the 224 phones sampled using this technology (95%). The most common 4G network technology is LTE (Long Term Evolution) with 56% (125/224) phones sampled using this technology. The other access technologies are CDMA (Code Division Multiple Access) and its successor EV-DO (Evolution-Data Optimized), competing standards to GSM offering 3G connectivity. HSPA and later LTE networks are two examples of data-transmitting networks that allow users to upload and download data wirelessly and that represent the exponential evolution of wireless data transmission rates. Access to these networks is determined by both the phone carrier, with different carriers providing access to different networks of varying capabilities, and the abilities of the mobile phones to support different networks (Dahlman et al. 2010). In 2009, the most common mobile technology network was GSM (Global System for Mobile Communications), a 2G network, with 16/17 (94%) of phones sampled making use of this network. In 2017, 100% of the phones sampled that year had access to GSM as well as LTE, and 31/32 (97%) had access to HSPA.

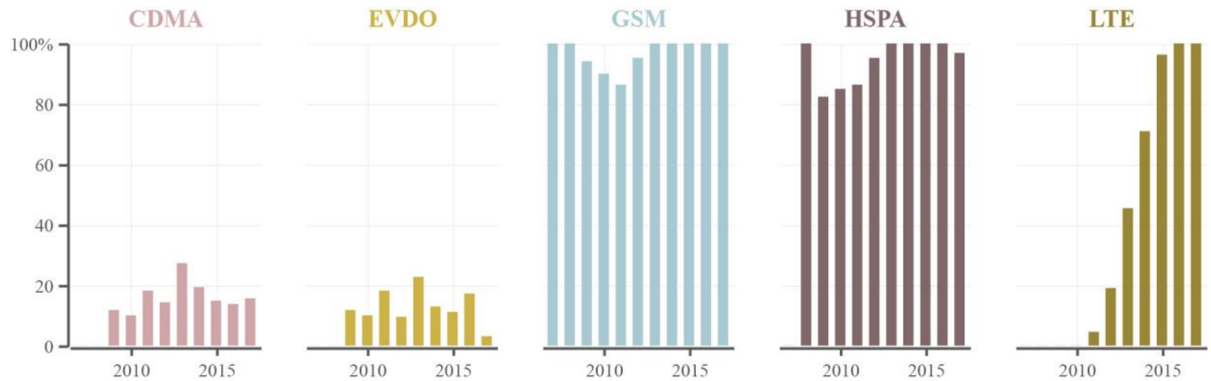

Figure 2.1: Overview of percentage of smartphones sampled each year with access to individual network generation technology.

Network Speed refers to how quickly users are able to access data on their smartphone over a mobile network. As Figure 2.2 shows, 3G networks in the sample topped out at 42.2 mbps (megabits per second), the maximum data transfer rate achievable with HSPA technology under optimal circumstances. The latest 4G networks allow for data download rates reaching upwards of 1,200 mbps (1.2gigabytes) as of 2017. While 4G network speeds have been increasing exponentially since their introduction, as illustrated in Figure 2.1, it must be noted that these are idealized speeds. 4G networks also have a marked negative impact on battery life that should be considered when designing applications that need to tap into these faster data networks (Huang et al. 2012).

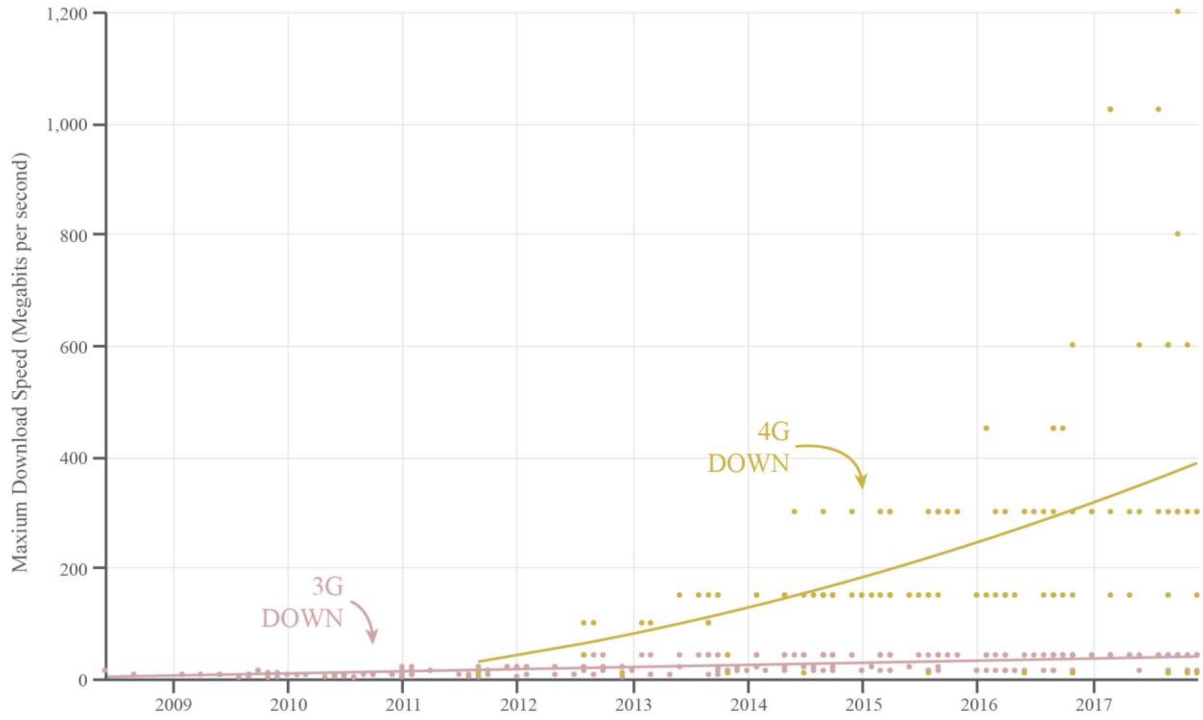

Figure 2.2: Maximum download speeds by available by network generation.

In practice, the experience of consistent high-speed coverage is limited by the physical distribution of cell towers, other users accessing the network, and the network provider. Mobile data is not always accessible to everyone, and mobile users are limited by coverage, carrier, and cost. Many of the phones sampled represent the 'flagship' phones of their representative manufacturers and likely were built to give the best possible performance that year. Those who choose not to spend nearly $1,000 on a smartphone (the cost of the iPhone X in 2018), or choose to use a carrier with less than optimal coverage in their region, will not achieve the idealized data rates characterized by the sample profiled in this thesis.

2.2.2 Constraint: Battery Life

The mobility of smartphones is a function of their internal power source, but this means the usefulness of the device ties directly to the length of time the internal battery can support use. Without power, the map cannot be viewed and the user is lost, a critical issue impacting user navigation and safety. Batteries often are considered one of the greatest limiting factors on the design and performance of smartphones, especially because their degradation over time can put increasing restrictions on smartphone performance (Saxena et al. 2017).

Mobile mapping applications can have a significant impact on battery life due to their reliance on constant connectivity to GPS and mobile data networks. In the case of navigation apps, for example, the need to keep the screen active in suboptimal lighting conditions can cause a device to run out of power before a destination is reached. Battery life impacts traditional cartographic design in several ways. Mobile map designers must consider the usefulness of their map while it is both actively being viewed and not viewed, how much energy the use of their map will consume, and how long they can reasonably expect users to engage with their map to achieve a task when the battery life of a smartphone is limited.

I collected three specification codes related to battery life: battery capacity, battery endurance, and replaceability. ***Battery capacity*** describes the amount of energy, measured in milliampere hours (mAh), stored in the phone battery. Milliampere hours describes the amount of time the battery lasts as measured against its discharge current (Android Authority 2019). GSMArena also provides a measure of ***battery endurance***, a benchmark measure of how long a phone can be used on a single charge if in that time the user makes one hour of 3G calls, spends one hour watching videos, and one hour browsing the web (GSMArena). Battery endurance better emulates the experience of using a smartphone in everyday conditions. Finally, there is the problem of battery degradation over time, because battery capacity decreases as the battery ages. This problem sometimes can be overcome through replacing this battery with a second external battery, but this is only possible if the smartphone was manufactured with a case that opens to allow the user access to the battery.

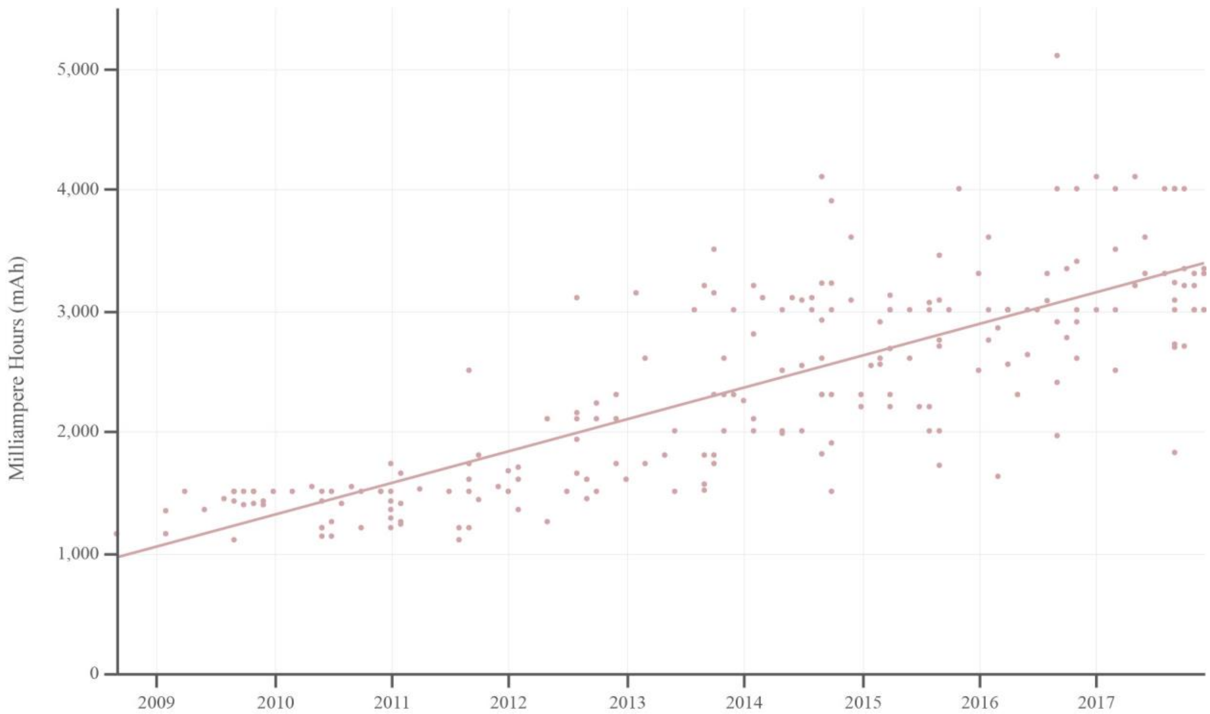

Figure 2.3: Sampled smartphone battery capacity in mAh over time.

<u>Battery Capacity</u>

Battery capacity has increased steadily over time, as Figure 2.3 shows. In 2009, the first year that the Android operating system began to hit the mainstream, the average smartphone sampled had a battery capacity of 1400 mAh. The average battery capacity of phones sampled in 2017 was 3,266 mAh. In the past decade, the average battery capacity has more than doubled, increasing 233.29%. Battery capacity is not directly correlated with how long a smartphone will last over the course of a single use, however, since batteries begin to age on first use and lose capacity over time. Batteries also are not discharged slowly and steadily while doing a single task, and the experience of using a smartphone, and by extension, a mobile map is much more variable. Some of the most common smartphone tasks that drain battery include connectivity tasks to WiFi, Bluetooth, or a cellular network, the screen display brightness, the color the screen background (dark displays use less energy than light displays), phone calls, video playback, and gaming (Perrucci et al. 2011).

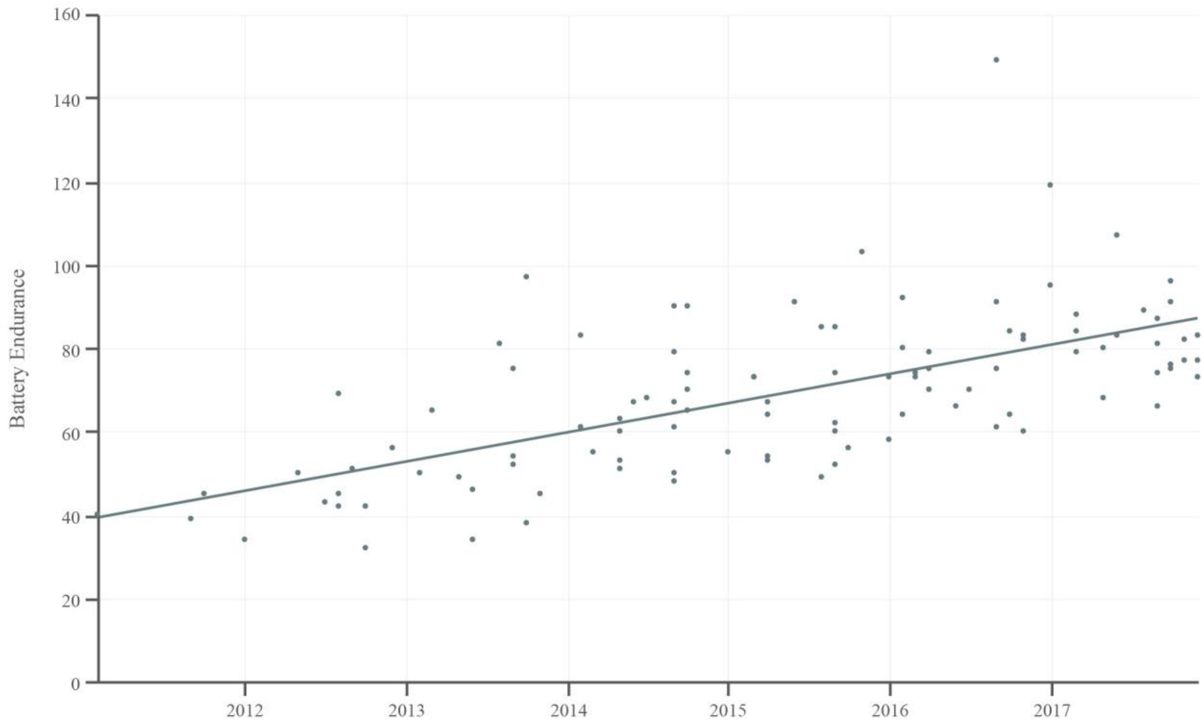

Figure 2.4: Sampled smartphone battery endurance rating over time.

<u>Battery Endurance</u>

Using GSMArena's battery endurance rating as a benchmark of typical use of the sampled mobile phones (Figure 2.4), experienced battery life has improved battery over the past decade, but not quite as much as battery capacity. In 2011, the first year GSMArena provided endurance ratings, the average rating of devices sampled was 41.33 hours. In 2017, the average endurance rating of sampled phones was 83.9 hours, over double that of the 2007 sampled phones (203% increase).

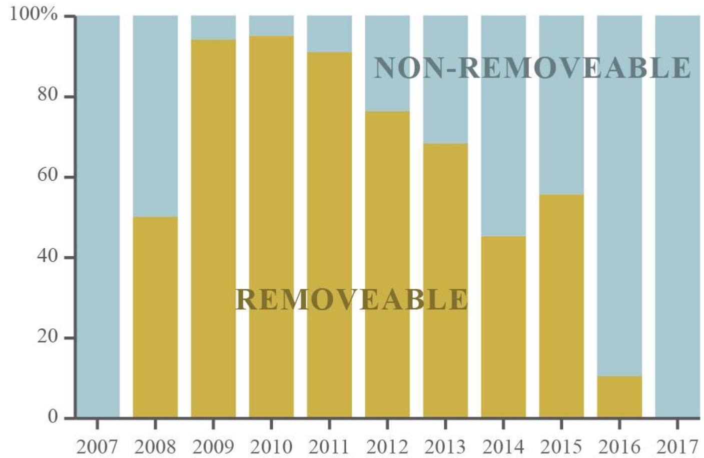

Figure 2.5: Smartphones with easily removeable and replaceable batteries over time.

Battery Replacement

One solution to the gradual decline of smartphone battery capacity over time is to allow for the battery to be easily replaced, usually by allowing for the back of the smartphone to be removed. Traditionally, iPhones do not allow battery removal. As can be seen in Figure 2.5, 94% of sampled mobile phones in 2009 had a removable battery and, by 2017, none did. The planned obsolescence of smartphone batteries often necessitates replacing the entire device if the battery degrades to the point where the user determines that it interferes with the use of the device. Inability to replace a battery poses consequences for mobile mapping applications, as previously it was possible to carry a spare battery for the devices as a means of guarding against being stranded when a phones battery runs out. While external battery packs are gaining popularity, it cannot be relied upon for you user to carry one, and battery life remains a critical consideration for mobile map design.

2.2.3 Constraint: Screens

As the primary means of viewing and interacting with smartphones, screens play an outsized role in how map users come to understand and interpret mobile maps. Screens also are the primary draw on smartphone battery power, and the type and size of the screen has a substantial impact on the overall experience of using the smartphone (Perrucci et al. 2011). Small screens can pose a challenge for the map readers when the mobile map interface becomes cluttered, confuscating important map symbols and interactive functionality, or when interactions become difficult to control due to the reduced size of the interface. Large screens, however, can interfere with ease of using the smartphone for a variety of hand sizes, reducing portability, and drain battery life. The variable nature of mobile screens creates a unique challenge for traditional cartographic considerations such as map composition, layout, generalization, typography, the inclusion of map elements, and interaction, requiring responsive cartographic design solutions across these displays (Roth et al. 2018).

Mobile screens present a unique challenge to developers and designers due to the highly variable nature of screen size, resolution, and aspect ratio. ***Screen size*** refers to the total area of the screen and is measured in square inches, giving a general sense of how much overall screen real estate a cartographer has to work with at any given time. ***Screen resolution*** differs from screen size in that not all screens of equal size can display the same amount of information due to variations in pixel density. ***Screen-to-body ratio*** describes how much of the smartphone face is made up of screen as related to the body of the phone. to Finally, ***screen aspect ratio*** refers to the overall dimensions of the smartphone and the relationship between the width and the height of the screen. Designing for a thin and narrow screen poses different challenges for a cartographer than a screen that is more compact and square, or a screen that has pieces cut away, curved, or is in other ways not perfectly rectangular.

Screen Size

Figure 2.6 shows that mobile smartphone screens have been steadily increasing in size since the introduction of the smartphone. In 2009, the average screen size (measured diagonally) was 3.36 inches. By 2017, the average smartphone was 5.58 inches. Accordingly, smartphone screens on average have grown by 2.22 inches in 11 years, an increase of 166%.

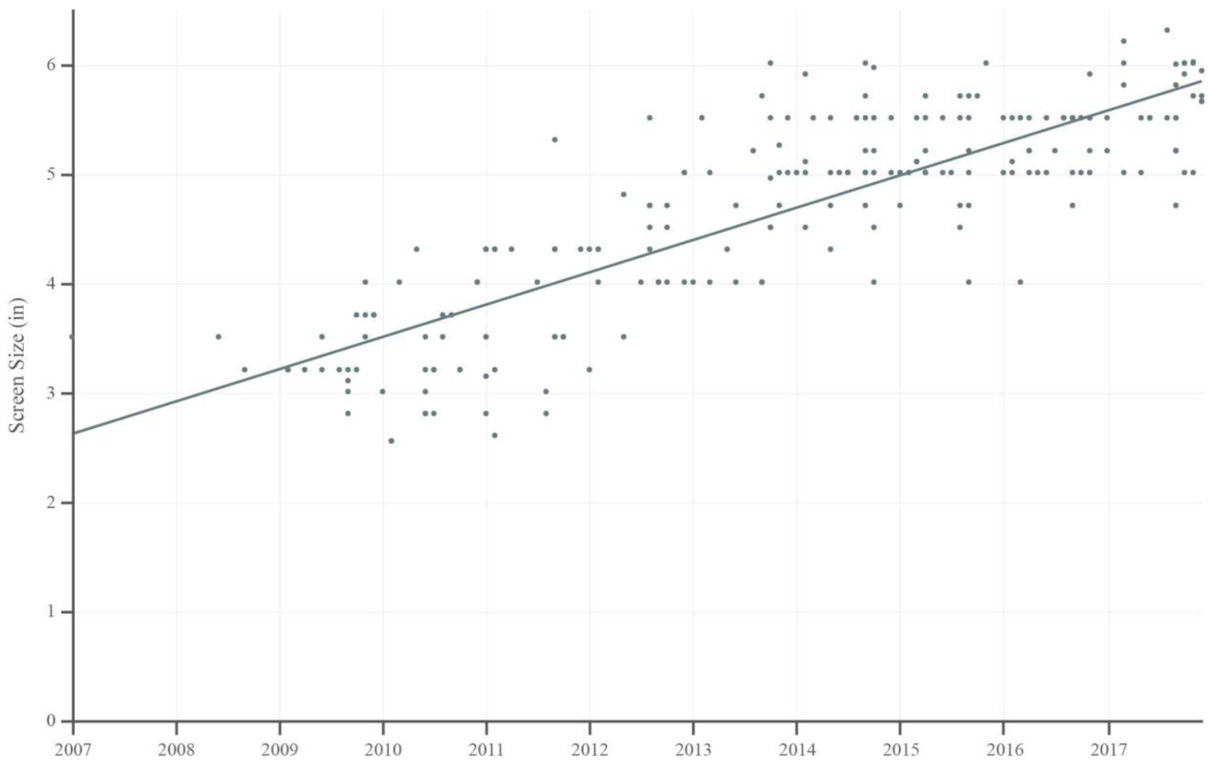

Figure 2.6: Diagonal length of smartphone screen sizes over time.

Screen-to-Body Ratio

As the size of smartphone screens have increased, the overall size of the smartphone has not kept pace, as Figure 2.7 shows. Looked at another way, while smartphone screens increased in size, the overall size of the phones sampled did not increase at the same rate. Instead, the surface area around the smartphone screen (the bezel) has shrunk. In 2009, the average screen took up 49% of the phone face. In 2017, screens on average took up 74% of the available smartphone face, and many popular phones featured screens even larger than this. The screen of the Samsung Galaxy S8+ taking up 84% of the face of the smartphone. The shrinking of the bezel implies that other physical means of interacting with the smartphone (i.e., buttons, speakers, notification lights, etc.) have moved from the face of the device to the sides or back, or they have been eliminated entirely.

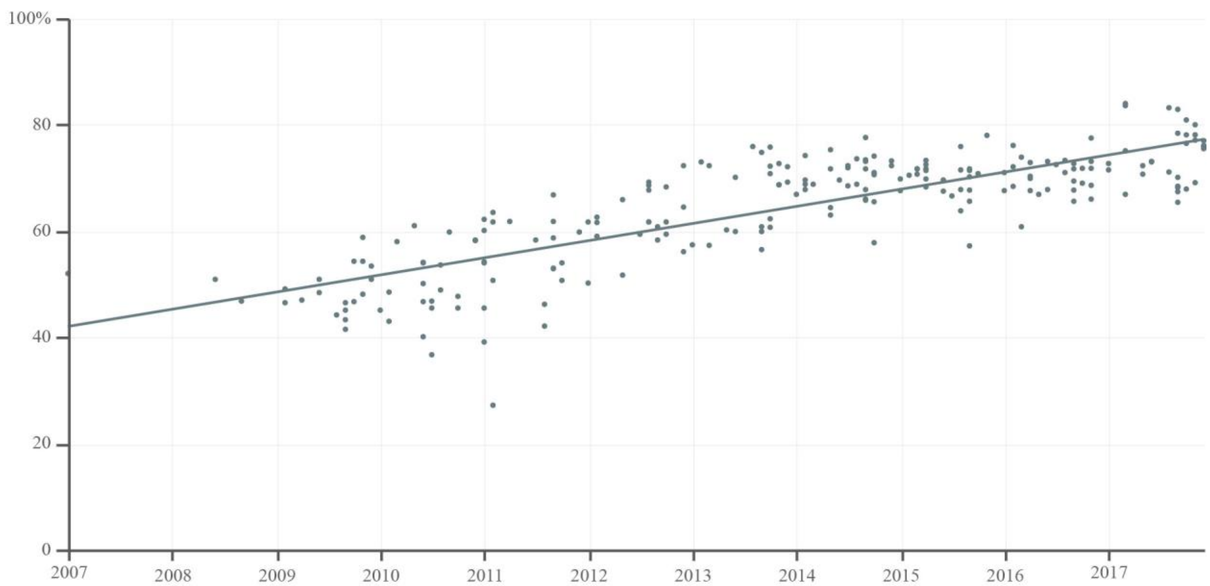

Figure 2.7: Percentage of screen to non-screen surface on the smartphone face over time.

<u>Screen Resolution</u>

Screen resolution describes the number of pixels that make up the two sides of an image. For example, the standard for a “High Definition” resolution is 1,280 pixels by 720 pixels, regardless if the screen belongs to a TV or a phone. Figure 2.8 clearly shows that, even though the physical size of phones is beginning to taper off, the pixel density of these screens is still rising. In 2009, the average smartphone had a pixel density of just over 207 pixels-per-inch (ppi). By 2017, this number had almost doubled to 386 ppi (187%). An increased number of pixels means that even if there are downward limits of how small text and icons can appear on a map to remain legible, these map elements can be can be displayed crisply and specialized raster design effects such as text halos can be employed effectively for overall design legibility. However, interface elements, despite being clearer on improved resolution, may be too small to interact with reliable using finger-based input, and thus may require larger pixel footprints to maintain the same physical screen footprint.

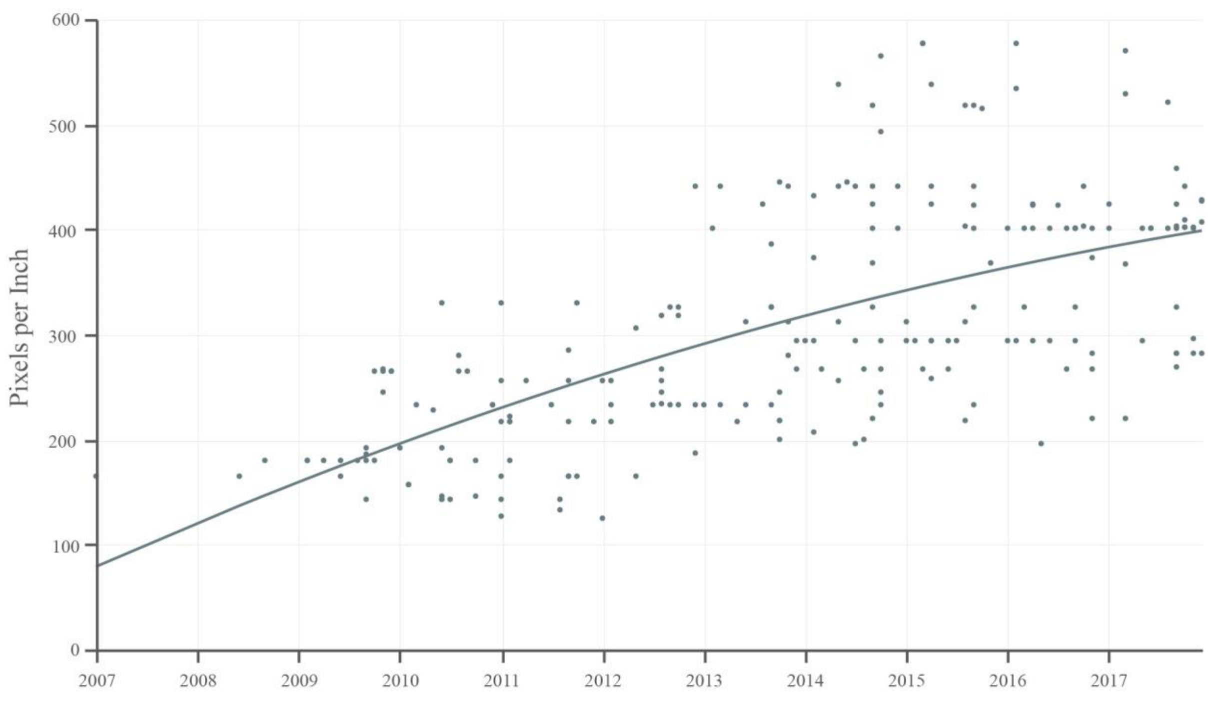

Figure 2.8: Smartphone screen pixel density in pixels per inch.

Screen Aspect Ratio

In addition to the trend towards slightly larger and more pixel dense mobile displays, there also has been a move in recent years away from the traditional 3:2 aspect ratio for smartphone screens to the more elongated 16:9 display, and, in 2017, to an even narrower 18:9 ratio as shown in Figure 2.9. In 2007, the majority of sampled smartphones (10 of 17; 59%) had an aspect ratio of 3:2. By 2017, the majority of sampled phones (17 of 32; 53%) had switched to an aspect ratio of 16:9.

A prominent complication caused by this variance in aspect ratios is the recent introduction of “the notch” first introduced with Andy Rubin’s Essential Phone and then popularized by the in the 2018 iPhone X design. Apple, in the design of the iPhone X, stated that their goal was to create an iPhone “that is entirely screen. One so immersive the device itself disappears into the experience” (iPhone X). In practice, designers must now account for clipping of their apps by the notch, creating even more variability for the placement of app elements (and by extension, map elements) than there was when screens were consistently rectangular despite aspect ratio variations. Elongation and irregularities in screen shape impact egocentric navigation interfaces, as now even less information is displayed on either side of the map for wayfinding context.

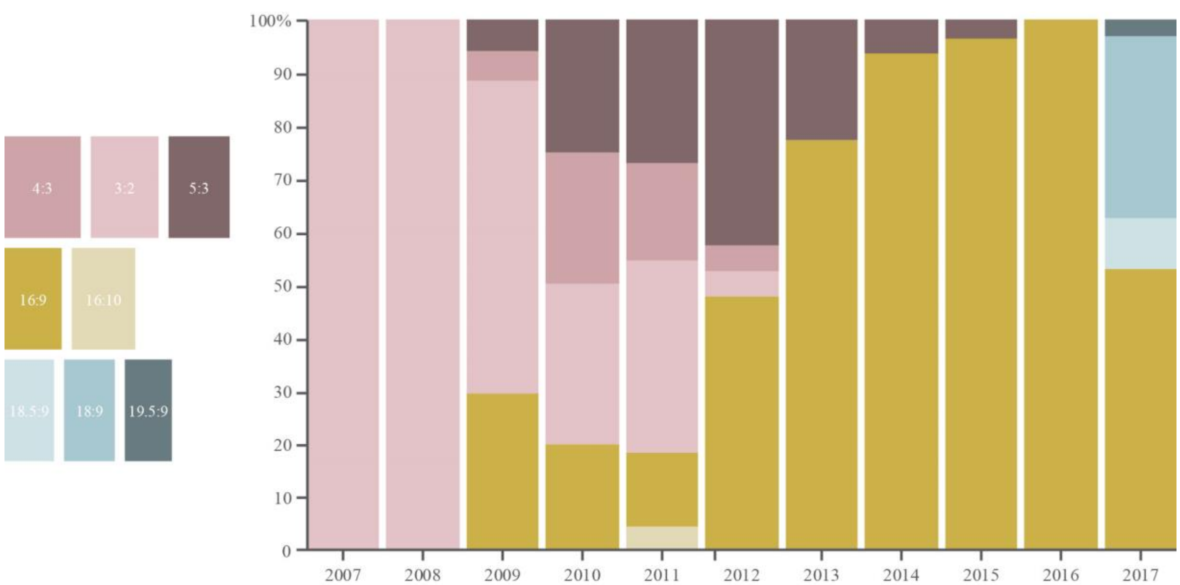

Figure 2.9: Change in smartphone screen aspect ratios in devices over time.

2.2.4 Constraint: Screen Viewing Conditions

Related to the screen specifications are the viewing conditions when using the smartphone. Viewing conditions describe the variable environmental context within which a smartphone may be used. For example, a mobile map might travel from indoors and artificial light to outdoors and bright sunlight, enter and exit a moving vehicle, and encounter a variety of weather conditions, all during a single use with a single user. Not only must the smartphone function in all these environments, so must the map. The map needs to remain legible to the user to continue being useful, and a key factor in constant legibility is the screen response. The legibility of the mobile map is a product of both the viewing medium (i.e., the type of touchscreen and the physical properties of the screen) and the resulting contrast ratio produced by the viewing medium.

I collected three specification codes related to viewing conditions: *screen type, indoor contrast ratio,* and *outdoor contrast ratio*. The ***screen type*** describes the type of display used in the manufacture of the smartphone. Advances in screen type technology greatly impact how legible the screen is in different viewing conditions as well as the overall battery life of the phone. ***Contrast ratio*** describes the ratio of the luminance of the brightest color (white) to the darkest color (black) that the system can produce. In the context of smartphone screens, luminance is a measure of brightness that describes how bright light emitted from a surface appears. GSMArena calculates contrast ratios by dividing the luminance of a pure white screen by the luminance of a full black screen set to 50% brightness. The higher the contrast ratio, the more vibrant the resulting image (Kaiser 1971). ***Outdoor contrast ratio*** describes the legibility of a screen in bright outdoor conditions. GSMArena calculates outdoor contrast ratio using the internal sunlight legibility test, which determines the contrast ratio in a simulated bright sunlight environment with the brightness of the smartphone turned up to 100%. Outdoor contrast ratio takes into account the reflectivity of the smartphone screen, which can have a drastic impact on the display of full black, and therefore the ability to read the screen in bright environments ("GSMArena Feature Labs: The Tests").

<u>Screen Type</u>

The technology behind smartphone screens has undergone three major transformations in the past 11 years as can be seen in Figure 2.10. TFT (thin-film transistor) displays are a variant of LCD (liquid crystal display) technology that uses active matrix technology to light individual pixels within the screen. In 2009, TFT LCD displays were the most prominent screen type of the phones sampled, with 82% (14/17) of the smartphones using TFT displays. Over the years, the use of TFT displays in the sampled phones has declined, and by 2017, none of the smartphones in the sample used this display type.

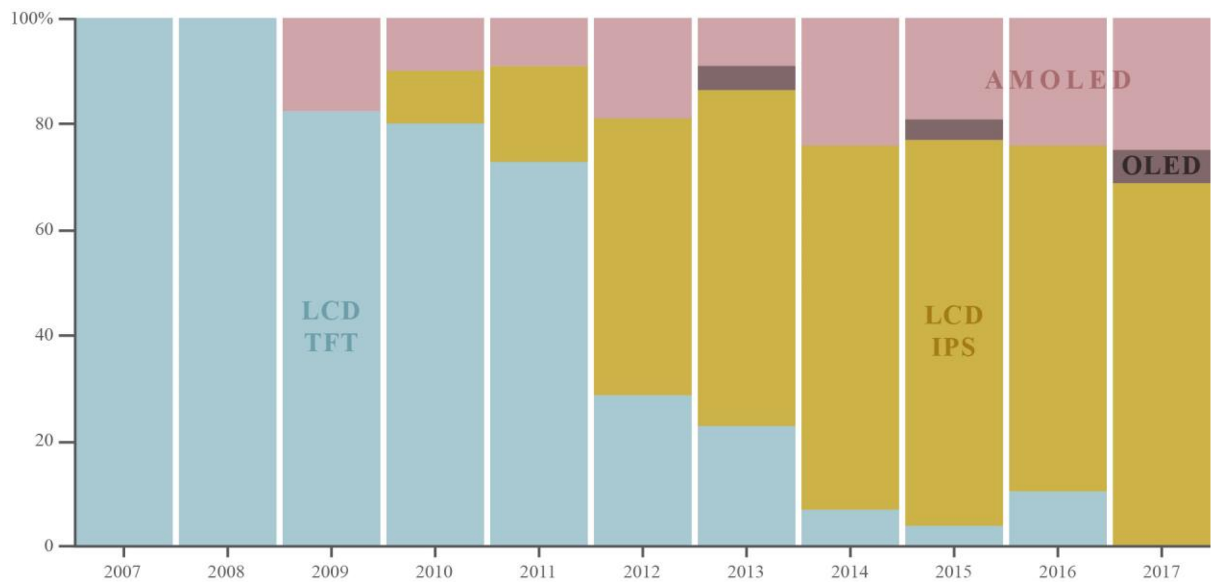

Figure 2.10: Percentage of phones sampled with common smartphone screen types over time.

As the use of TFT displays declined, the improved LCD technology of IPS LCD has risen. Overall, IPS screens are the most common screen type in the sample with 111 (50%) of the sample using this screen type. IPS (in-plane-switching) is an improvement on TFT LCD technology that provides increased viewing angles, increased screen response times, and improved color reproduction and representation in the screen (“TFT vs. IPS Display: What’s the Difference?” 2017). This screen type was first found in the sample in 2010, with two of the 20 (10%) sampled phones that year utilizing this technology. By 2017, 69% (22/32) sampled phones contained IPS screens, becoming the most prominent LCD technology in the sample.

The third screen type found in the sample, OLED (and by extension AMOLED) screen technology has become slightly more prominent over the years, but remains less common than LCD technology. AMOLED screens are a more common variation of OLED technology that combines some features of TFT displays to create an “active matrix” of organic diodes. In 2009, 18% (3/17) of the phones sampled had AMOLED displays. This number had risen slightly by 2017, with 25% (8/32) phones sampled having AMOLED screens, and 6% (2/32) with OLED screens.

OLED and AMOLED (organic light-emitting diode and active-matrix organic light-emitting diode) screens produce images by utilizing electroluminescent material and, in the case of AMOLED screens, an active matrix. This differs from LCD screens because AMOLED screens utilize organic materials as opposed to LCD’s liquid crystals. AMOLED are thinner, lighter, and more flexible than LCD displays. They are also brighter because the organic materials used are much thinner and do not require glass for support, allowing more light overall to be emitted than the inorganic LCD crystals. An important difference that impacts the contrast ratio of the sampled screens is that AMOLED pixels do not need backlighting due to the bioluminescence of the utilized materials, and instead emit light directly. This results in significantly less power consumption of the screen compared to LCD screens, as well as better viewing angles and an infinite contrast ratio due to AMOLED display's ability to completely switch off black pixels. These advantages come with a cost however, because the AMOLED organic materials have a limited lifetime, are easily damaged by water, and are more expensive (Purohit, Banu, and Daiya 2012).

Contrast Ratio

As shown in Figure 2.11, nominal (indoor) contrast ratios, excluding displays with infinite contrast ratios, have been steadily increasing over time. The higher the contrast ratio, the easier it is to read the screen, and these high numbers reflect that these screens were highly legible in indoor environments. In 2009, the contrast ratio of the Apple iPhone 3GS (the only sampled smartphone tested that year) was 201. In 2017, the average contrast ratio of phones sampled that year was 1,549, an 770% increase.

Outdoor Contrast Ratio

This differs greatly from the contrast ratios determined from testing in sunlight-like conditions as can be seen in Figure 2.11. While phones generally are becoming more legible in bright sunlight environments, smartphone screens in 2017 are still on average 99.77% less legible outdoors than phones from the same year in dark environments. This trend is unlikely to change anytime soon due to how reflective glass is in sunlight. In 2010, the average outdoor contrast ratio of the phones sampled that year (no phones in 2009 were tested by GSMArena) was 2.6. In 2017, the average had only risen to 3.5 (a 134% increase).

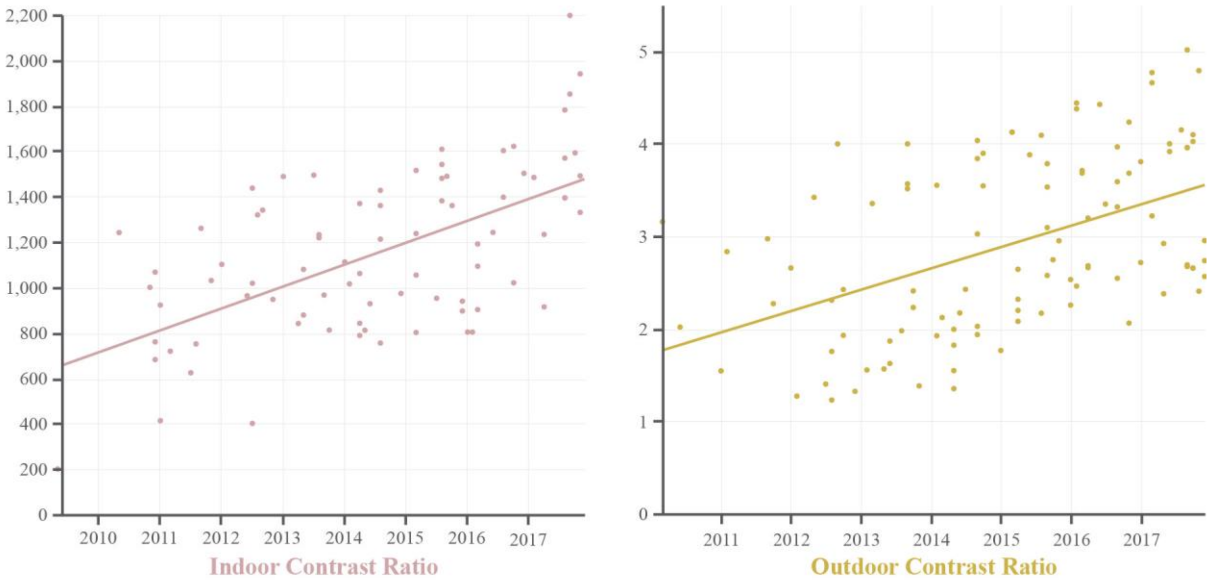

Figure 2.11: Indoor and outdoor contrast ratios as a measurement of screen visibility in varying environments over time.

2.2.5 Constraint: Processing Power

As the promise of ubiquitous computing becomes a reality enabled by modern smartphones, users increasingly expect their smartphone to behave as both phone and computer. This is especially true regarding the demands put on the performance and expectations around the computing capabilities of smartphones. Users want to run multiple processes simultaneously and seamlessly. Processing power in smartphones is an important determinant of how quickly the smartphone can perform tasks, such as opening an app or rendering JavaScript on a webpage. The smartphone's processor impacts how quickly a device performs tasks and how responsive and immersive the act of using the smartphone feels for the user.

Processing power in smartphones is a product of the embedded ***processors*** included with the device. It is now standard for phones to come with two processing chips, *central processing units* (CPU) and *graphic processing units* (GPU). The speed at which these units can process data is then a product of technical development as well as physical structure of the unit. Recently, more advanced chipsets have been developed to respond to increasing data processing demands by adding multiple cores to increase their ability to process data in parallel (Lee et al. 2010). When considered together, these two components of the smartphone reflect the processing capabilities of the phone, but the two chipsets still perform slightly different roles in the mobile medium, and the overall speed of the device can depend on how applications utilize them.

Central processing units (CPUs) and Graphics Processing Units (GPUs) have a large impact on smartphone performance as well as power consumption, in some cases almost as much as the smartphone screen, but they are also necessary for a smartphone to operate quickly and responsively (Kim and Chung 2013). The GPU is generally designed with many small processing elements to handle many small tasks in tandem, like changing screen pixels quickly to display graphics, while the CPU is designed to be more general and able to run many types of applications (not just visual ones) but relies on additional cores to handle data in tandem (Lee et al. 2010). Increasingly, GPUs are utilized for non-graphical tasks because of their ability to perform many tasks simultaneously. Because of this ability, GPUs are commonly thought to be faster than CPUs, but with a diminished ability to process or cache large amounts of data (Lee et al. 2010).

GPUs enhance user experience through improvements in the display and speed of graphical user interfaces (GUIs). In the past, GPUs and CPUs were thought to have a negligible impact on overall power drain in smartphones, but as processors become more powerful and include multiple cores, they have begun to impact battery life through becoming increasingly power hungry (Kim and Chung 2013). For mobile map designers, this means that complicated design demands placed on in the map GUI as well as large amounts of data processing should be considered for the potential impact they can have on the overall smartphone battery drain (Carroll and Heiser 2010). For example, an interactive map rendered in 3D would place a much higher demand on the phone's GPU than a 2D map. Map developers need to consider how much data is being displayed on the map and at what speeds it need to be rendered, what kind of graphics are necessary, and how quickly not only can the smartphone process and display the data, and if there are any optimizations that can be made in their code that can speed these processes.

For mobile maps, this means that the lag time between requesting and displaying information decreases as the computing power of the smartphone increases. The smartphone also needs to be capable of both displaying a map that is constantly updating and adjusting as the smartphone moves, while also simultaneously performing tasks such as spatial searches and playing music. Improvements in processor power therefore directly correlate to improvements in the mobile mapping experience. While improved processors will improve information request and display, connectivity will continue to act as a bottleneck for map use in suboptimal network conditions due to the limitations on the speed at which data can be received before processing.

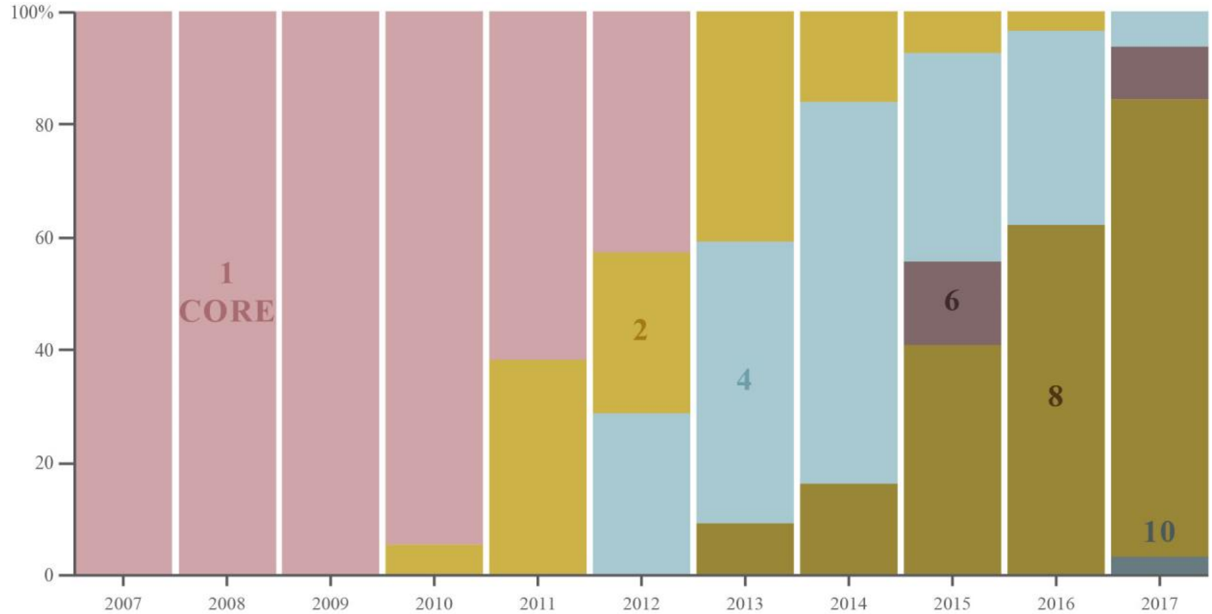

Figure 2.12: Number of CPU Cores in sampled smartphones over time.

Figure 2.12 shows that beginning in 2010 mobile phones began including multiple CPU cores, and by 2013 all phones in the sample had at least two CPU cores. In 2009, all phones sampled had a single CPU core. By 2017, the average smartphone had eight cores and the Lenovo K8 Note had ten. This marks an exponential increase in the number of CPU cores included in mobile phones and serves as a proxy for the subsequent increase in mobile smartphone processing power generally, especially for performing multiple tasks simultaneously as well as for handling larger amounts of data.

2.3 Enablements

The smartphone as a physical computing device enables mobile mapping through providing unique interactivity options compared other computing devices, through their mobility, and through their location awareness. An overview of these enablements is provided in Table 2.2. The following section explores the influence of these enablements have on mobile maps, summarizes how the design of smartphones has changed over time, and provides a short history of GPS. I aim to provide insight into both how mobile map designers might better utilize the physical hardware of smartphones in the design of mobile maps as well as to understand how the design of these devices might be change in the future.

Table 2.2: An overview of mobile mapping enablements related physical design of smartphones.

Enablement	Code	Definition
Unique Interactivity	*Speaker*	Device included in a smartphone that produces audio output to be heard by the listener.
	Microphone	Device included in a smartphone that captures audio and converts the sound waves into an electrical signal.
	Bluetooth	Shortwave communication technology that can be used to connect smartphones to other Bluetooth enabled devices.
	Vibration	A smartphone alert type where the device is physically moved by a small internal electric motor.
	Haptic visualization	The encoding of information through touch.
Mobility	*Locational Sensors*	Smartphone sensors that enhance its location awareness capabilities.
	Accelerometer	Locational sensor that detects how quickly a device is moving
	Gyroscope	Locational sensor that detects the pitch and roll of the device
	Compass	Locational sensor that detects the cardinal direction the device is pointing
	Barometer	Locational sensor that can detect elevation changes
GPS	*GPS Receiver*	Locational sensor that detects the location of the device using a gnss
	GNSS	Global Navigation Satellite System, a network a satellites used to triangulate user location
	A-GPS	Assisted GPS, a GPS signal that has been augmented with WiFi or cellular data to improve locational accuracy.

2.3.1 Enablement: Unique Interactivity

Unlike traditional desktop computing environments, smartphones are unique in the multitude of ways that they demand the attention of their users. Through a variety of sensors, feedback mechanisms, and unique interaction possibilities, the experience of using a smartphone for mobile mapping becomes conversational in a way that traditional point and click computing or the experience of using a paper map is not. The user requests information and the smartphone responds, reminds, and updates in response to the query often without additional user input. It is in this way that the smartphone expands on the mobile map as visual representation to the mobile map as immersive medium. By taking advantage of the smartphone as a medium for a multisensory experience, the mobile map becomes imbued with the potential for unique approaches to thinking and decision-making (Griffin 2001; Roberts et al. 2014). The building blocks of this multisensory experience are the visual/aural, tactile, and kinesthetic forces that together make interacting with a smartphone unique. These components can be broken down into a series of potential input and feedback mechanisms in the form of sound, voice, kinesthetic forces, and light (Fritz and Barner 1999).

<u>Auditory Interaction</u>

Of these potential mechanisms for unique interactivity, perhaps none are more essential for the use of the smartphone than the speaker/microphone combination. ***Speakers*** are devices within the smartphone that produce audio output that can be heard by the user. Conversely, ***microphones*** are included sensors that capture audio input and convert it into an electrical signal that can be ‘read’ by applications within the smartphone. *Speakers* and *microphones* provide the user with a means of interacting with the smartphone through sound. All sampled mobile phones were equipped with a speaker and microphone. Smartphone speakers commonly are used to alert the user of new notifications, but this is not their only use for mobile map design. Smartphone microphones can be employed to enable map interaction through voice commands for manipulating the map. Sound can be a useful way of augmenting visualized information or encoding additional information into a map (Krygier 1994).

At the time of writing, there are several popular virtual personal assistants that can be installed on smartphones, employing the phone's speaker and microphone for hands-free interaction. Reaching the mainstream with the introduction of Apple's Siri in 2011, virtual assistants have been gaining widespread popularity and changing not just how users interact with their smartphones, but how people interact with the interconnected Internet of Things beyond the smartphone. The most popular virtual assistants are Google Assistant and Apple's Siri, but it is also possible to use Amazon's Alexa, Samsung's Bixby, and Microsoft's Cortana as conversational interfaces to interact with a variety of phones and other devices. These interactions include obtaining information using voice search such as finding restaurants, getting directions, setting alarms, and placing phone calls (McTear, Callejas, and Griol 2016). In a mobile mapping context, these virtual assistants mean that it is now possible to use a smartphone for navigation without looking at a visual depiction of physical space, complicating what might be considered a mobile map versus not.

Bluetooth

In addition to speakers, all phones sampled came equipped with Bluetooth. ***Bluetooth*** is a short range communication technology that is commonly used to connect the smartphone wirelessly to other Bluetooth enabled devices (Perrucci et al. 2011). As Figure 2.13 shows, new Bluetooth versions quickly are adopted by smartphones. Bluetooth 5.0 enables phones to increase their range and communicate with multiple devices at once, and is an important component of internal positioning systems, all while draining less power from the connected devices (Hoffman 2018; Leonard 2019).

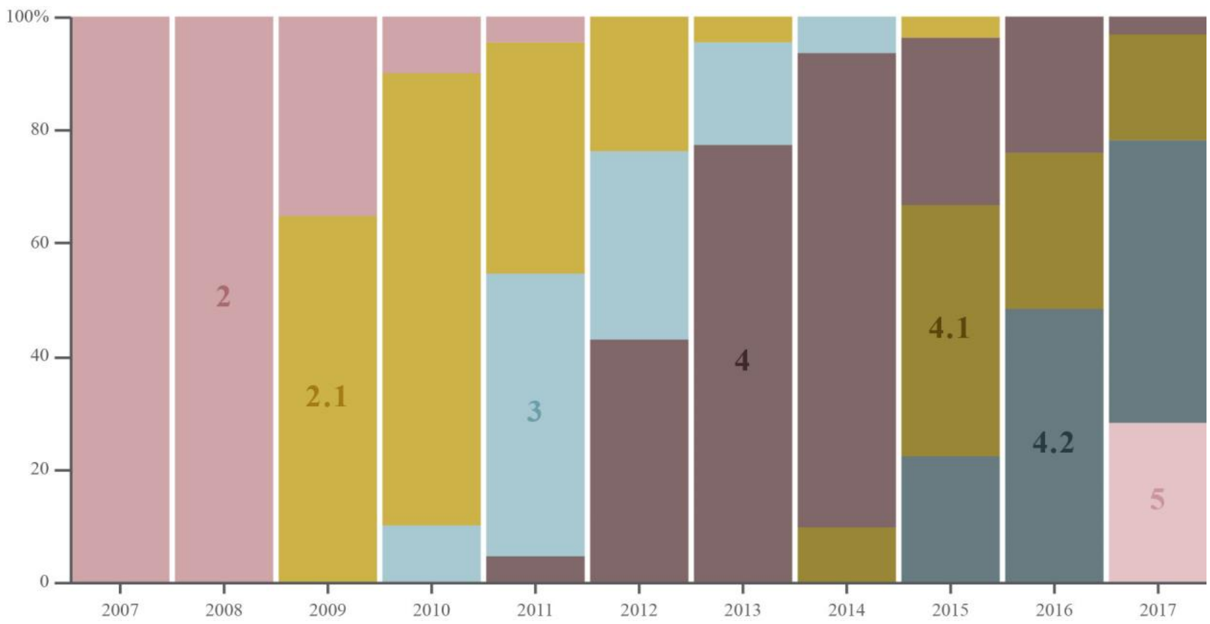

Figure 2.13: Bluetooth versions utilized in sampled smartphones.

Being Bluetooth enabled further integrates the smartphone into the larger Internet of Things (IoT) ecosystem and expands the capabilities and sensors available to the user beyond those present in the smartphone alone. Bluetooth is commonly used to connect to wireless headsets, speakers, and wearable trackers (“2019 Bluetooth Market Update” 2019). This has implications for mobile mapping because Bluetooth connectivity can be used to extend and augment the capabilities of the smartphone to other devices. For example, the popular Apple Watch can be used to provide haptic feedback to extend a navigation task given to a smartphone, a feature made possible through Bluetooth connectivity. Bluetooth is used to connect devices because it drains less battery than other means of pairing devices over a mobile network such as 3G or WiFi ("About Bluetooth, Wi-Fi, and Cellular on Your Apple Watch").

Haptic Feedback

Every sampled smartphone also included ***vibration*** as an alert type. Vibration is now so ubiquitous in smartphones that GSMArena no longer codes it as a feature of mobile phones. The inclusion of vibration for representation in a mobile medium is particularly interesting because it enables multimodal input and feedback, expanding the capability of the smartphone (Griffin 2001). ***Haptic visualization*** describes the encoding of information through a sense of touch, traditionally including both tactile perception (feeling textures) and kinesthetic perception (feeling forces on the body). Haptic visualization should be understood as an augmentation of the visualization medium, since such tactile displays enhance, but can never convey as much information as a traditional visualization (Fritz and Barner 1999). In a mobile mapping context, this means that a wayfinding app could simultaneously visually indicate that the user should turn right, use sound to say "turn right," and vibrate in such a way that indicates that the user should make a right turn, creating an immersive wayfinding experience that reduces errors through effective redundancy and enables customization of user preferences. Haptic visualization also moves the map further from a solely visual medium, having implications for both sighted and non-sighted users.

Many smartphones also are equipped with small LEDs reserved to alert users to notifications without needing to turn on the screen. GSMArena does not code for the inclusion of this feature, so it is not possible to specify which sampled phones make use of notification lights through the presented method design. These small lights commonly are located on either the front or the rear of the phone. The Android API allows for applications to define their own notification light behavior, but this behavior is limited to the color of the light and the on/off duration (Harrison et al. 2012). This constrained behavior and limited application offers little to contribute to the immersive mobile mapping experience.

2.3.2 Enablement: Mobility

Smartphones are unique in the sheer number of *locational sensors* that are included a daily-use device. ***Locational sensors*** are sensors housed within the smartphones that specifically extend the location awareness capabilities of the smartphone, enabling mobility (Ricker 2019). The mobility of the smartphone means these sensors travel with the users and create unique mobile mapping opportunities. The mobility of the sensors also present new map design limitations, most notably the loss in accuracy that accompanies with the shrinking down and constant movement of the sensors included in the phone, especially those most useful for navigation. For example, the compass (magnetometer) included in 84% (190/224) of the sampled smartphones is the only sensor that can accurately identify which way is north relative to the phone, but these readings are easily distorted by large metal objects such as cars, electric power lines, and large buildings (Blum, Greencorn, and Cooperstock 2012). Table 2.3 presents a complete list of the unique sensors included in the sample.

Table 2.3: Unique sensors featured in sampled smartphones

Mobility Sensor	**Count**	**%**
Accelerometer	224	100.0%
Proximity	210	93.8%
Compass	190	84.8%
Gyro	106	47.3%
Barometer	40	17.9%
Fingerprint (Rear-Mounted)	36	16.1%
Fingerprint (Front-Mounted)	31	13.8%
Heart Rate	10	4.5%
Spo2	9	4.0%
Temperature	4	1.8%
Gesture	4	1.8%
Iris Scanner	3	1.3%
Color Spectrum	2	0.9%
Humidity	2	0.9%
Face Id	1	0.4%
Uv	1	0.4%

As Figure 2.14 shows, there is a trend for smartphones to include increasing numbers of sensors, many of which directly impact the phone's mobility and expand its potential uses in mobile mapping applications. Many of the observed sensors are of interest to mobile map developers because they support orienting capabilities for a location-aware device, as well as expanding the capabilities of the mobile map and increased the granularity of sensed data.

The most common sensor included in smartphones is the ***accelerometer,*** a sensor that detects how quickly the device is moving. Initially introduced to enhance the user interface experience and use of the camera (they allow the smartphone to know which way it is are oriented and adjusts the display accordingly), accelerometers also can automatically detect different activities such as running, biking, or walking when they are done with the smartphone on the user's person. The ***gyroscope*** and the ***compass*** expand the GPS sensor capabilities through sensing pitch and roll and north, respectively. These sensors fine-tune the phone's awareness to be not just where in space the smartphone is, but which way it is oriented and in which direction it is moving (Ricker 2019). The ***barometer*** can detect elevation changes including different floors while inside (Lane et al. 2010). Of the phones sampled, 100% included an accelerometer, 84% included a compass, 47% included a gyroscope, and 17% included a barometer (useful for knowing elevation). As Figure 2.14 shows, the number of sensors included in mobile phones, and specifically those related to mobility have been increasing rapidly. In 2009, on average phones included 2.3 sensors (accelerometers and either proximity or compass sensors), and by 2017, the average smartphone had 5.0 sensors, a 217% increase.

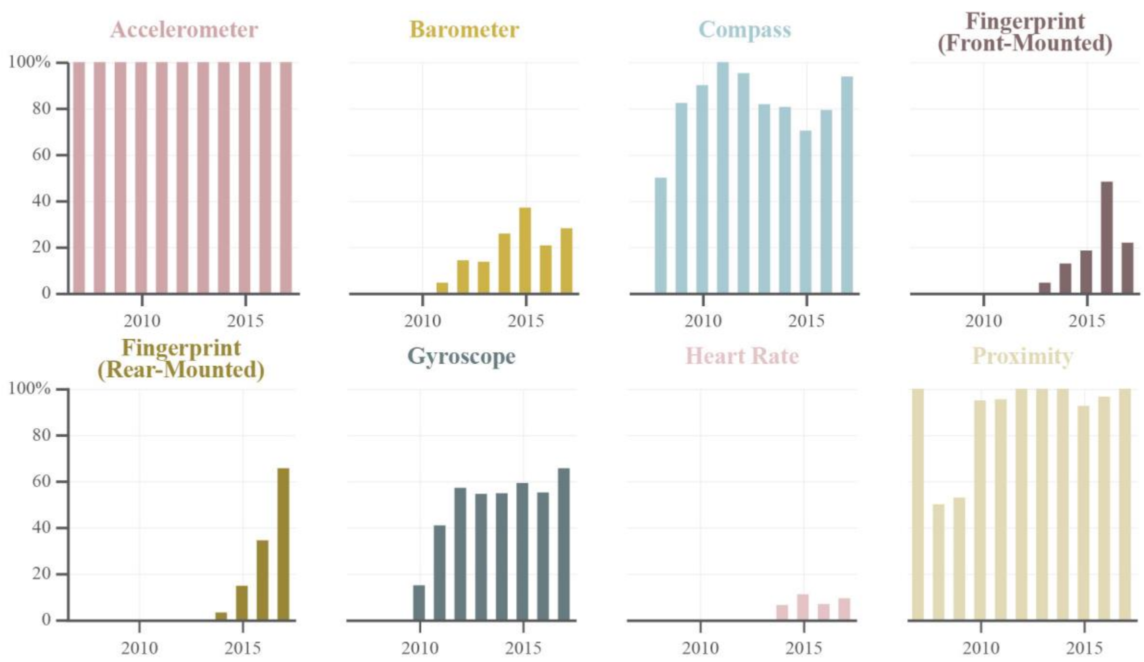

Figure 2.14: Locational sensors included in sampled smartphones over time.

2.3.3 Enablement: GPS

The most important component of a mobile map is the ability of the map to be aware of where it is in space. It does so by utilizing ***GNSS*** (global navigation satellite systems), the most popular of which is ***GPS*** (The Global Positioning System). GPS is a U.S. owned utility that is developed, maintained, and operated by the U.S. Air Force ("GPS.Gov: GPS Overview"). A GPS receiver is included in all smartphones on the market today. Location awareness has become an essential component of smartphones and the key component to enabling mobile mapping as we know it. But, location-aware smartphones are a relatively recent phenomena building upon two distinct technological advancements.

History of GPS

The first advancement was creation of the GPS satellite network. Originally called Navstar GPS, this system was launched by the U.S. military starting in 1974 and completed in 1994. Mobile cartography for navigation first became widely available to the public in 2000 after the United States Department of Defense ended the purposeful degradation of GPS signals for public use. As a result, GPS transmissions became 10 times more accurate overnight, enabling rapid expansion of location-based services (LBS) (Lawler 2000). Location-based services are the result of a system that incorporates the users location as a variable in the information system, providing targeted information to the user based on their location. When mobile map users are using a mobile map to interact with or further understand their environment, they are using LBS (Gartner and Uhlirz 2005; Dao, Rizos, and Wang 2002).

Through the early 2000s, GPS technology continued to get smaller and cheaper, and by the mid-2000s, the market was saturated with portable GPS devices utilizing location-based services, but these devices were narrower in their utility than contemporary mobile phones (Lendino 2012). These newly shrunken GPS sensors were much easier to integrate into consumer systems and started to become standard in mobile phones. GPS is not necessary for location awareness, some systems are capable of utilizing Bluetooth and WiFi for indoor navigation, and WiFi and Cell Id numbers can also provide clues to user location, but it is a critical component of most systems. The first mobile smartphone to include GPS technology was the Benefon Esc!. Manufactured in 1999 and sold mainly in Europe, the Esc! lacked access to the internet and the capabilities of this smartphone to utilize LBS were limited because un-augmented GPS signals become inaccurate in urban areas and indoors. The Esc! did allow users to preload maps into the smartphone to trace their location, and even share their coordinates via SMS, providing an early prototypical glimpse at some LBS that have become standard today. As more mobile devices became location aware, pushed by an FCC requirement needed to determine the location of 911 calls, wireless operators and businesses both were looking to monetize these advancements and appear more attractive to users. For example, in May 2000 the Japanese company J-Phone launched the J-Navi service, creating one of the first mobile location-based interactive mapping services. J-Navi was revolutionary in that it allowed users to display a map within a web browser on their smartphone and search within 500 meters of the user for a phone number, address, or landmark (Ahmad 2015; Dao, Rizos, and Wang 2002).

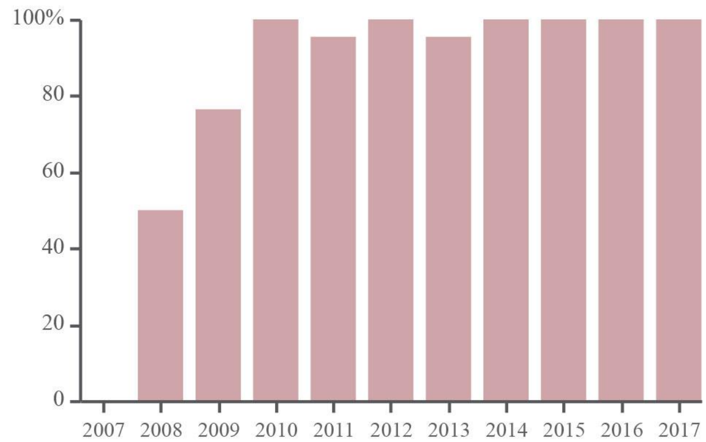

Figure 2.15: A-GPS access over time.

A-GPS

The second technological advancement that enabled GPS to become accurate enough to meet consumer demands was the invention of ***A-GPS***. In 2004, Qualcomm developed “assisted GPS” (A-GPS) technology that allowed phones to combine GPS with their cellular signal to improve the accuracy of the device location. As noted in Figure 2.15, A-GPS has become standard on phones with access to 3G and 4G networks, with 76% of phones sampled in 2009 having access and 100% of phones sampled in 2017 using this technology. The invention of A-GPS led the way for accurate, widespread access to a phone’s location in real-time and for LBS to become a standard smartphone feature (Sullivan 2012). Despite the progress in recent years, GPS and A-GPS should not be considered as perfectly accurate. As Blum et al. (2012) found, there are a number of accuracy issues for the location and orientation sensors found in current smartphones. For example, GPS sensors (using A-GPS) exhibit errors between 10 and 30 meters depending on the surrounding buildings. This error is experienced by users as the mobile map appearing to have worse performance in more urban areas, and a reduction in trustworthiness overall.

GNSS

The United States GPS system is not the only global positioning system accessible to mobile phones. Several other countries also have launched or are in the process of launching their own GNSS (global navigation satellite systems), many of which are accessible to mobile devices outside of the country that operates the system. These global international GNSS are China's BeiDou (BDS), the EU's Galileo, and Russia's GLONASS. Several countries also have launched GNSS intended to supplement coverage in a specific region such as India's IRNSS and Japan's QZSS (Alkan, Karaman, and Sahin 2005; "Other Global Navigation Satellite Systems (GNSS)" 2017). Increased access to these systems means that the devices utilizing more than one GNSS network experience improved positioning accuracy, signal availability, and system integrity (Alkan, Karaman, and Sahin 2005). As more of these systems come online, support is being rapidly added for smartphone access, as can be seen in Figure 2.16. In 2009, the average smartphone had access to a single GNSS: GPS. By 2017, the average smartphone had access to 2.7 GNSS networks.

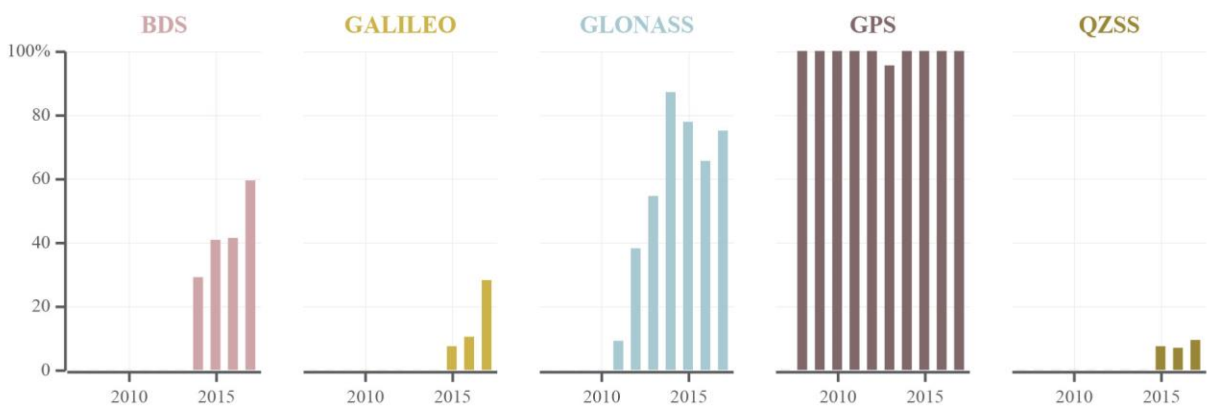

Figure 2.16: Smartphone access to various global navigation satellite systems.

<u>User's Location Representation History</u>

But, GPS is only a tool to be utilized by LBS. As the National Coordination Office for Space-Based Positioning, Navigation, and Timing is keen to point out: "GPS only gives you the blue dot. It does not provide the map!" (NCO 2017). As these services became pervasive, private companies began to develop proprietary map interfaces customized to specific user needs. Google Maps was launched in 2005, and that same year “Google Maps for Mobile” launched to enable users to get directions on the go (Agar 2013). The blue dot followed in late 2007 with the introduction of the “My Location” feature that enabled users to automatically have the map center on where they were located and search based on proximity to their location in real-time. The blue dot utilized to represent user location in Google Maps is one example of an egocentric mobile map view. Other ways of embedding the user within the mobile map include visualizing locations that are of interest to the user and adjusting the map view to reflect user direction (Meng 2005).

As GPS technology continues to get smaller and increasingly accurate, it has gone from something tightly regulated by the entities who own the GPS satellites to a service expected of our smartphones. At the same time, mobile “phones” have evolved from the clunky satellite phones in the 1980s and 1990s to sophisticated pocket-sized computers explored above capable of doing much more than making phone calls (Wolpin 2014). The shrinking of the cell phone and the advances in display technology, combined with the shrinking of and increasing sophistication of all the sensors and technology, as well as advances in the physical hardware of phones has opened the doors for the creation of the ubiquitous mobile mapping landscape we all inhabit today. The ability to display maps on smartphones that are easily readable, interactive, and location aware is unique to the past decade of mobile development and one ripe for further scientific exploration.

CHAPTER 3: QUANTITATIVE CONTENT ANALYSIS OF MOBILE MAP DESIGN

3.1 Method: QCA of Mobile Map Data, Representation, and Interaction Design

3.1.1 Overview

This chapter describes the second of two content analyses I completed on mobile mapping, the latter providing a systematic evaluation of the cartographic design of mobile maps. This second content analysis was informed by and speaks back to the Chapter 2 study investing the enablements, constraints, and evolution therein, of smartphone technology on mapping applications. Specifically, I assessed design choices for data, representation, and interaction, interpreted how these related to the Chapter 2 enablements and constraints of the smartphone, and provide discussion on how current mobile map design is taking advantage or missing some of the unique opportunities provided by smartphones.

I used quantitative content analysis (QCA) to evaluate the design of 36 mobile maps as they were available on the Google Play App Store in late June and early July of 2019. I again choose QCA because of its ability to quantify design and usefulness of visual products, enabling the quick comparison and quantification of design across a sample (Muehlenhaus 2011). I provide additional details about the use of QCA for cartography in Chapter 2 and do not repeat here. The following subsections describe the process for selecting the sample of mobile maps, the schema by which the maps were evaluated, and the process for analyzing the resulting data.

3.1.2 Mobile Map Sample

I collected the sample of 36 mobile maps using a combination of two app ranking aggregation websites: AndroidRank.org and SensorTower.com (2019). The sample consists of apps available to both Android and iPhone, but I included or excluded prospective mobile maps using the app's rankings in the Google Play store due to its browser-based access on the open web; Apple Store ratings are only available through Apple products and software, limiting access.

AndroidRank.org is as one of the oldest tracking sources of Google Play store smartphone app history data (as self-reported by the website) and one of the only sources that provides historical information for free ("AndroidRank" 2019). Many other app ranking websites charge for the service, including SensorTower.com. AndroidRank.org also is unique in that it supports sorting by the official "achieved install" frequency counted by the Google Play store, data Google itself does not make readily available. Because "achieved installs" does not reflect if and when an app is *uninstalled*, the achieved installs tally only can go up and gives preference to older apps, apps that come preinstalled, and apps that once were very popular but have since decreased in popularity or are no longer being maintained. I therefore complemented the AndroidRank.org list with free data from SensorTower.com to create a snapshot of contemporary popularity in the moment, providing an alternative look at where mobile map design may be headed. SensorTower.com aggregates the daily Google Play store rankings by category and supports filtering by region, features that the Google Play store does not support.

Table 3.1 provides a list of categories included in the sample and associated mobile maps. Sampled categories include: Adventure, Education, Events, Finance, Food & Drink, Health & Fitness, House & Home, Lifestyle, Maps & Navigation, Medical, News & Magazines, Parenting, Shopping, Social, Sports, Travel & Local, Weather, Art & Design, Auto & Vehicles, Beauty, Books & Reference, Business, Comics, Communications, Dating, Entertainment, Libraries & Demo, Music & Audio, Personalization, Photography, Productivity, Tools, Video Players & Editors. Categories not sampled due to a lack of a highly ranked mapping app include: Art & Design, Auto & Vehicles, Beauty, Books & Reference, Business, Comics, Communications, Dating, Entertainment, Libraries & Demo, Music & Audio, Personalization, Photography, Productivity, Tools, Video Players & Editors.

Table 3.1: All sampled apps and their corresponding Google Play Store categories

Category	**App Name**
Adventure	Wizards Unite, Pokémon Go
Education	PlantNet, PlantSnap
Events	Stubhub, Gametime
Finance	Capital One, Bank of America
Food & Drink	Zomato, Starbucks
Health & Fitness	Samsung Health, AllTrails
House & Home	Trulia, Zillow
Lifestyle	Life360, happn
Maps & Navigation	Uber, Waze, ParkMobile, Lyft
Medical	Weedmaps, Leafly
News & Magazines	Citizen
Parenting	Find My Kids
Shopping	Groupon, OfferUp
Social	Facebook, Snapchat
Sports	onX Hunt, Fishbrain
Travel & Local	Google Street View, Booking, Google Earth, Google Maps
Weather	The Weather Channel, AccuWeather

To balance the sample, I selected two apps from each of the Google Play store “categories”. First, I used AndroidRank.org “achieved installs” sorting feature to determine the most popular mobile app containing a map *of all time* in each sampling category. I then used SensorTower.com to determine the most popular app containing a mobile map in each category on *July 4, 2019*. If the same app appeared as top ranked in both AndroidRank.org and SensorTower.com, I then selected the second ranked app within the category on SensorTower.com.

I coded four total mobile maps for two of the Google Play store categories—Travel & Local and Maps & Navigation—because of the overrepresentation of mobile maps in these categories. I only coded one app from the Parenting category because the most popular mobile maps in this category were child tracking apps, raising location privacy concerns. I also only coded one app from the News & Magazines category, as only one app from the category included a map.

3.1.3 Procedure

After collecting the sample of 36 apps, I analyzed the design of these mobile maps drawing both on mobile mapping literature and from my own analysis of smartphone enablements and constraints. First, I established a series of codes with which to evaluate the sample by adapting the interactive cartographic design thinking workflow as described by Tolochko (2016), which itself was derived from Donohue's (2014) prototypical web map design workflow of *data→representation→interaction*. Here, ***data*** covers the functionality of the mobile map as it relates to outside data sources and the types of data utilized, what data is required for functionality of the map, and the ability of the map to meter or alter those data requirements. ***Representation*** describes how maps are seen and understood through their appearance, and ***interaction*** describes the conversation between the user and the map as the user completes tasks with the map (Donohue 2014; Roth 2012). I adapt this established web cartography framework for mobile to explore where mobile maps conform to and digress from established interactive web map design conventions.

I then organized a total of 69 codes into three subcategories: Data Characteristics (RQ 4a), Representation Design (RQ 4b), and Interaction Design (RQ 4c). I then further subdivided each category of codes to capture specific themes. The Data Characteristics codes cover common GIS and sensor datasets mapped in mobile apps as well as contextual data needed for the maps to functions (e.g., GPS-based location). The Representation Design codes capture design choices that inform the overall look and feel of the map, the different kinds of basemap and thematic representations available in the mobile mapping app. Finally, the interactive elements of the map were recorded using Roth's (2013a) interaction operator primitives to gauge what actions users were able to perform while engaging with the map. I provide a list of codes and their definitions at the start of each subsequent section of Chapter 3.

3.1.4 Analysis

I coded the sample over a two-week period between June 22, 2019 and July 7, 2019. I applied codes as text entries in Microsoft Excel. Generally, I noted codes as a binary stem of 'Y' and 'N' to reflect the inclusion of the code in the map in a quickly legible manner, and then converted to 1 or 0 for subsequent quantitative analysis. I recorded ten codes using a "free write" section for cross referencing and note taking purposes. I calculated descriptive statistics of the codes using the Python library pandas and generated graphs from these statistics using the Python library Altair, cleaning the graphics in Adobe Illustrator. All analysis code is available on Github (https://github.com/LeanneAbraham/thesis). Appendix A contains the results of this analysis.

3.2 Data Characteristics

The Data Characteristics category of codes explores the general data requirements and characteristics of the sampled mobile maps, including both the types of data the apps display and data requirements of running the apps. Table 3.2 provides a summary of the Data Characteristics codes and their frequency across the sample.

Table 3.2: Summary of numerical data characteristics codes

Category	Code	Definition	Count	%
GIS Data	*Points*	The map includes point data/features as non-basemap layer(s)	34	94.4%
	Lines	The map includes line data/features as non-basemap layer(s)	11	30.6%
	Polygons	The map includes polygon data/features as non-basemap layer(s)	12	33.3%
Sensor Data	*GPS*	The map requires GPS access to function	32	88.9%
	Positioning	The map provides the location of the mobile user by connecting to the network operators positioning system	30	83.3%
	Geographic Search	The map searches for geographic features	27	75.0%
	Routing Service	The map calculates the shortest or fastest route between two points or a number of points (current position, address, POI) and direction instructions (street names, distances, and turns)	7	19.4%
	Geocoding Service	The map determines X and Y coordinates for relevant POIs or addresses	6	16.7%
	Proximity Search	The map finds nearest POI or POIs nearby from a position or address, e.g. the nearest bus stop, ATM, drugstore, post office etc.	26	72.2%
	Reverse Geocoding	The map converts coordinates into a geographic text format	6	16.7%
	Other Sensors	The map requires access to additional sensors (accelerometer, gyroscope, etc.) to function	8	22.2%
Non-Spatial Data	*Text Results*	The interface (not the map) displays search results text/non geographic information	23	63.9%
	Multimedia Information	The map includes multimedia information like images, text, sound, etc.	21	58.3%
	Events	The map displays an event that is happening in real time	13	36.1%
Data Conservation	*Data Reduction*	The map limits its accuracy to conserve battery	3	8.3%
	Offline Mode	The map can be downloaded and used offline	5	13.9%

3.2.1 GIS Data

The first set of codes within the Data Characteristics category cover foundational GIS vector data types as well as emerging sensor data sources available on smartphones. In a vector data model, all georeferenced data comprises X and Y coordinates and results in three data types defined by how these coordinates are connected (Longley et al. 2015). A ***point*** consists of a single node and accordingly demarcates a single instance of a phenomenon. A ***line*** consists of a sequence of node connected by arcs, with the order of nodes defining the shape of the line. Finally, a ***polygon*** consists of an enclosed loop of nodes defining the boundary of the polygon. Accordingly, I included three codes within the GIS Data subsection covering points, lines, and polygons. I did not code for raster data characteristics, the alternative data model to vector in in GIS, because of its infrequent use within the sample and the difficulty of determining the difference between rasterized vector data on the mobile map and actual source raster data. However, I did encounter what appeared to be raster data overlays in both mobile maps from the Weather category: *The Weather Channel* and *AccuWeather*.

<u>Points</u>

Across the sample 94% (34/36) of the mobile maps utilized point data in some form. The pervasive inclusion of points is largely due to the common inclusion of ***points of interest*** (***POIs***) markers on mobile maps to support spatial search and wayfinding, a pattern that reappears in the Representation Design and Interaction Design codes. The two apps that did not use point data in some form were *OfferUp* and *The Weather Channel*, the former utilizing polygon AOIs to visualize areas where goods are located, while the latter relying on raster weather data overlays as described above. A fascinating use of point data was employed in the app *Fishbrain*, where users could report the fish they caught and where (Figure 3.16). In a refreshing departure from many of the other sampled mobile maps that heavily leaned on the use of point icons to represent businesses, *Fishbrain* instead pointed people to where they could acquire a resource that did not cost money, fish.

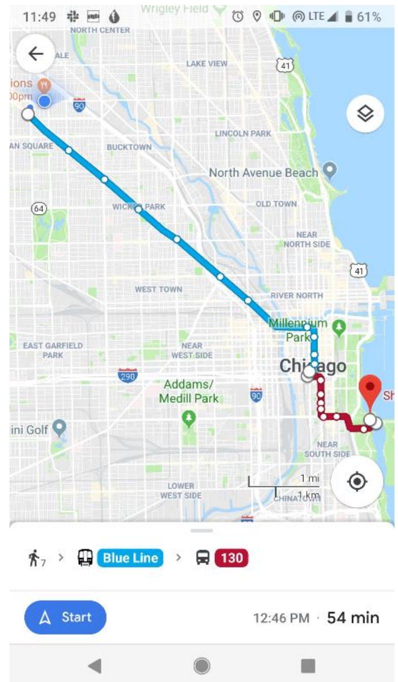

Figure 3.1: Lines being used for routing in Google Maps.

<u>Lines & Polygons</u>

In contrast, 31% (11/36) of the sampled mobile maps utilized lines and 33% (12/36) used polygons. Only four sampled mobile maps included all three data types: *Google Street View*, *Google Earth*, *Google Maps*, and *onX Hunt.* Figure 3.1 showcases one example of how lines are employed in *Google Maps*, in this instance to represent public transportation. The lack of mobile maps that include more complicated GIS Data types such as multipolygons or complex lines represents a greater absence of thematic maps in the mobile map sample, and likely the mobile mapping landscape generally.

3.2.2 Sensor Data

The second set of codes within the Data Characteristics category captures use of Sensor Data. As discussed in Section 2.3.2, much of what enables the utility of a smartphone in changing, indoor-outdoor environments is the increasing array of sensors included in the smartphone. As introduced above, GPS is an important enablement of mobility, supporting

location-based services that tailor information and functionality based on the user's locational context (Huang et al. 2018; Reichenbacher 2004). Location-based services are not limited to a mobile map, as it is possible for mobile applications to be location-aware without visually representing this information in a map display. Given the importance of GPS and LBS, I included two codes to capture the use of Sensor Data by the mobile map itself: a first code for *GPS* in support of location-based services and a second code to capture access to any *other sensors* on the device used by the mobile map.

GPS

Notably, 89% (32/36) of the sampled mobile maps *required* access to the GPS sensor to function. The requirement is perhaps expected given the Chapter 2 finding that all the smartphones sampled in 2017 as investigated in Chapter 2 have access to the devices GPS. This ubiquity of GPS in the sample is consistent with market research and further blurs the line between location-based services and mobile maps (Anderson 2016).

The most common use (83%; 30/36) of the GPS sensor in mobile maps was for ***positioning***, enabling the user to identify their location on the map (following Reichenbacher 2004). Mobile maps that do not provide positioning services focused on travel or entertainment, presenting information about places the user was not currently located and requiring a ***geographic search*** to center the map before it is populated with information (e.g., Booking, StubHub). As discussed in Section 3.4, 75% (27/36) of the sampled mobile maps supported such a geographic search using GPS. Many (72%; 26/36) of the sampled mobile maps also leveraged GPS for ***proximity filter***, using a geographic search with a distance buffer to filter points of interest.

One of the common uses for mobile maps is to help the user get from point A to B using a ***routing service***. Notably, only 20% (7/36) of the sampled mobile maps used GPS to provide a routing service. While less common than expected, many of the sampled apps provided links to open other apps installed on the smartphone that specialize in routing. For example, *Zomato* provides routing services indirectly by linking their app to *Google Maps* and allowing for routing by opening in a separate app. Switching between apps on a smartphone can be problematic, losing essential data for wayfinding and forcing repeated reloading (Roth et al. 2018). However, such synergistic pairing of mobile maps may only grow as mobile operating systems provide improved functionality for switching between apps.

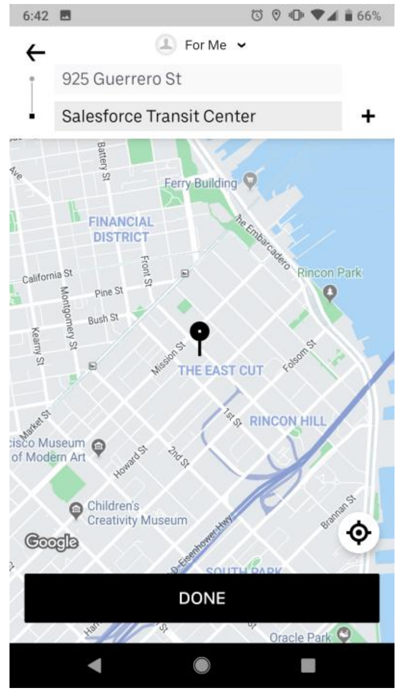

Figure 3.2: Reverse geocoding using a pin in Uber.

While less common, six of the applications sampled (17%) used GPS for geocoding services and reverse geocoding services to support routing. ***Geocoding*** is the process of converting addresses, commonly a street address, into geographic coordinates (such as latitude and longitude), while ***reverse geocoding*** is therefore the process of converting geographic coordinates into a human readable address (Reichenbacher 2004). Of the mobile maps that provided geocoding services, two were created by Google (*Google Earth* and *Google Maps*) and all were intended to be used for navigation. Only two mobile maps, *Uber* and *Lyft*, provided reverse geocoding capabilities that did not require the user to manually type in the coordinates of the location they wanted to navigate to, but instead allowed users to interactively move a pin that was then converted into an address by the app (Figure 3.2).

Other Sensors

Beyond GPS, 22% (8/36) of the sampled mobile maps also requested access to other sensors. As summarized in Section 2.1.2, 100% of smartphones now come standard with an accelerometer and more than 50% are manufactured with a gyroscope. While a frequency of only 22% suggests that mobile maps have yet to fully realize the potential of sensors beyond GPS, several innovative designs exist that support novel user experiences. For instance, the *Life360* app utilizes three sensors in addition to GPS—the accelerometer, gravity sensor, and gyroscope—for their "Driver Protect Plan", a subscription service that detects how quickly a car is moving and alerts emergency contacts if the user is in an accident. *Life360* also monitors smartphone usage while driving, a potentially useful data point given risks of split attention between texting and driving. Accordingly, constant collection of sensor data through mobile maps also presents new ethical concerns around location privacy as more dimensions of user mobility and behavior are revealed to private companies (M. W. Wilson 2012).

3.2.3 Non-Spatial Data

The inclusion of information that is not explicitly geographic within a mobile map enriches the map and provides context for the geographic data. Part of the design of all sampled mobile maps was the inclusion of data that was not explicitly geographic but that tied back to the geospatial qualities of the mobile map. This augmenting information came in the form of text, multimedia information, and temporal information.

Text

To understand how non-map text was employed within mobile maps, I made simple search queries or filters within each of the sampled mobile maps. Of the sampled mobile maps, 64% (23/36) displayed the results as text. For the search results to be considered a ***non-spatial text***, the text needed to directly relate to the search term and display of the map, but not displayed on the map. Typically, text results were displayed as a “popup” list that partially obscured the map with content relating back to the search results on the map (Figure 3.3). Non-map text generally referred to map POIs, often a list of businesses including their address, or otherwise a list of POIs displayed on the map providing additional information about map locations.

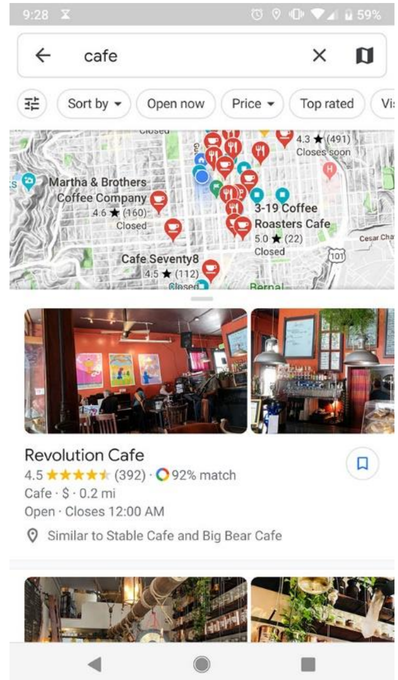

Figure 3.3: List and geographic search results in Google Maps.

Multimedia Information

True to the old adage, “a picture is worth a thousand words,” one of the most popular ways to extend the usefulness of geospatial data when contending with limited screen real-estate is through the inclusion of ***multimedia information***. For the sampled mobile maps, a search result was considered to include multimedia information if the result contained photos, videos, animations, or other interactive content that was not geospatial or text. Across the sampled mobile maps, 58% (21/36) included multimedia information in the results when queried. Figure 3.3 provides an example of multimedia information returned as part of a search query in the form of pictures alongside the text list. Most often, this information was a photo of searched item, and the inclusion other multimedia in mobile mapping applications remains an area for further study.

Events

Within a mobile map, an ***event*** is a dynamic and automatic display of new temporal information without a new user request for information. Across the sampled mobile maps, 36% (13/36) had the ability to display events. Events are highly engaging aspects of mobile maps because they continuously demand the user's attention and invite the them to engage further without first requesting a new map. The events in the sampled mobile maps varied widely, ranging from a Pokémon appearing as you approached it in *Pokémon Go,* to simulated cars driving around a ride hailing app. Events in the sampled mobile maps often were accompanied by unique feedback, which is explored further in section 3.4.3.

3.2.4 Data Conservation

When considering mobile, it often is the amount of data loaded into the mobile mapping app and not the format that is of chief concern given constraints on data plans and battery life imposed by the device. ***Data conservation*** therefore is the conscious decision on the part of the map designer to provide their users a chance to limit the data used by their mobile map, reducing the overall drain on the smartphone battery, while increasing mobile map usefulness in areas with poor data coverage and potentially saving their users money.

The data conservation set of codes includes two forms of conservation. First, the mobile mapping app can provide the option to reduce the amount of data used by allowing the user to specify how much data the mobile mapping application uses or limit the location accuracy of GPS-based features, both resulting in a ***quality reduction*** of overall user experience. Second, the mobile mapping app can provide an ***offline mode*** where the app continues to function without any new data inputs. It should be noted that the GPS receivers in a smartphone continue to function without an active connection to data since they can communicate directly with global navigation satellite systems, but access to A-GPS capabilities is lost and there is a reduction in overall locational accuracy.

Data Reduction

Surprising, only three of the sampled apps (3/36; 8%) enable users to conserve data and battery through a quality reduction: *Pokémon Go, Google Earth*, and *Waze*. As shown in Figure 3.4, *Google Earth* supports data usage reduction through its “rendering quality” feature, with lower rendering quality using less data. Similarly, *Waze* allows users to select the option to have their screen dimmed when their battery is low, provided there are no upcoming turns. *Pokémon Go* has a feature that dims the screen when held upside down, replacing the dynamic game screen with a static one, conserving resources until the smartphone is held upright again. Conserving data empowers the user to make their own decisions about the necessary functionality of the mobile maps and promotes inclusive design across data environments and user circumstances by lowering the cost of using the mobile map.

While uncommon within the sampled mobile maps themselves, data conservation often remains possible through the smartphone operating system. Android devices starting with version 7.0 include a “Data Saver” option built into the device, enabling users to control manually which apps have access to background data and the amount of data these apps require on a device-wide basis (“Optimize Network Data Usage”). Similarly, Apple includes several features in iOS that allow users to deactivate auto play for apps, select the quality of images that load over cellular data, and even remove access to cellular data for selected apps altogether.

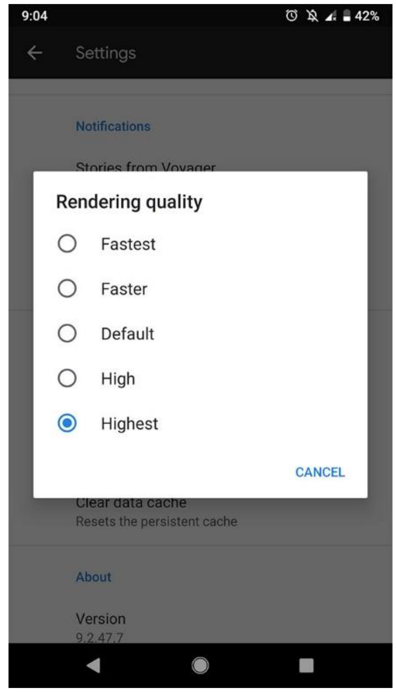

Figure 3.4: Rendering options in Google Earth, enabling the user to choose how much data *they want to use as well as the resulting impact on quality.*

<u>Offline Mode</u>

There were several more examples of an offline mode in the sampled mobile maps (14%; 5/36) than data conservation, although both features were underutilized. I evaluated the offline mode code by locating this mode in the settings or by deactivating data connectivity of the testing device and performing a search function in the app. Offline access was particularly common in *Travel & Local* and *Maps & Navigation* apps (e.g., *Waze, Google Maps*), likely because this functionality is extremely important for supporting wayfinding in locations with poor data connectivity (e.g., *All Trails, onX Hunt*). The fifth mobile mapping app—*Google Earth*—uses offline mode to access a large cache of low-resolution data stored in the system memory, and functions like an extension to low accuracy mode.

3.3 Mobile Map Representation Design

The Representation Design category of codes explores how information is represented in the mobile map. I explored four components of mobile map design: how map features were displayed within the map, which basemaps were included in the mobile map with a focus on which basemap was included as the default, the view and directionality of the map, and finally which map elements were included in the mobile map. Table 3.3 provides a summary of the Representation Design codes and their frequency across the sample. A well-designed information display system empowers the user and speeds the processing of map reading tasks, while a poorly designed one creates situations where the user is hindered, the map is difficult to use, or incorrect conclusions are made (Crease and Reichenbacher 2011).

Table 3.3: Summary of numeric representation and design codes

Category	Code	Definition	Count	%
Map Features	*Users Location*	The map includes the user's location as a map feature	30	83.3%
	Points of Interest	The map includes POI that can be interacted with as a map feature(s)	30	83.3%
	Regions of Interest	The map includes ROI that can be interacted with as a map feature(s)	12	33.3%
	Other Users	The map includes other users as map features	16	44.4%
Basemaps	*Basemap Colors - Dark Mode*	The map includes a 'dark mode' basemap option	9	25.0%
	Basemap Colors - Light Mode	The map includes a 'light mode' basemap option	33	91.7%
Map Views	*Default Orientation - North*	The map defaults to north is up regardless of user orientation	33	91.7%
	Default Orientation - User Forward	The map is centered on the users location and reoriented so that forward is not north but up.	3	8.3%
	Default Loading View - Egocentric	The map centers on a user's location as default option on load	23	63.9%
	Dimensionality - 2D	The map includes a 2-dimensional view	34	94.4%
	Dimensionality - 3D	The map includes a 3-dimensional view	18	50.0%
	Change on Rotation	The map layout adjusts when the phone is rotated from vertical or horizontal	8	22.2%
	Projection - Web Mercator	The map uses an the Web Mercator projection	32	88.9%
Map Elements	*Indications of Orientation*	The map includes a compass to orient the user	11	30.6%
	Indications of Scale	The map includes a geographic scale to measure distance	4	11.1%
	Legend	The map includes a key or legend to identify features	5	13.9%

3.3.1 Map Features

The first set of codes within the Representation Design category assess visual design solutions for the most common kinds of map features found in mobile maps, teasing out emerging design standards for mobile maps. I narrowed a large set of initial map features of interest down to four map features that particularly define mobile map representation: the user's location, points of interests, regions of interest, and the location of other users.

User's Location

One defining capability of mobile maps is their ability to make users constantly aware of their position, a GPS-driven feature described in Section 3.2.2 as positioning. The user's location typically is highlighted visually through a salient and dynamic map symbol, essentially embedding the user within the mobile map. This constantly-connected and constantly-*mapped* experience moves the map beyond just a depiction of reality, but instead makes the map a augmentation of reality that shapes the user's experience of that very reality (Wilson 2012). Thus, continuous representation of the user's location marks a major departure of mobile maps from paper maps and interactive but desktop-bound maps.

Of the sampled mobile mapping applications, 83% (30/36) represented the precise location of the user in the map. The six sampled mobile maps that did not represent user location instead utilized GPS and location-based services for other functions in the app but did not display this information on the map. Surprisingly, 76% (23/30) of sample apps representing the user's location did so with a blue dot within a white circle frame. A convention popularized through *Google Maps*, the 'blue dot' has come to be shorthand for the user's location in mobile maps.

Several of the sampled mobile map apps break from the ‘blue dot’ convention by instead using personified, highly mimetic icons, a solution that works to further embed the user in the map. The gaming apps *Pokémon Go* and *Wizards Unite* both employ highly personified avatars to represent the user as they move through the landscape. *Snapchat* uses a similar ‘bitmoji’ avatar to represent the user’s location, a cartoonish humanoid figure that can be altered to mimic the mobile map user’s facial features, personal style, and mood. Personification of the symbolic representation of the user’s location is a way of signaling the role of the user in the map, presenting a code for playfulness and enhancing user engagement (Thorn 2018). However, personified avatar icons may not always be good, potentially resulting in information clutter and privacy issues, both requiring future research.

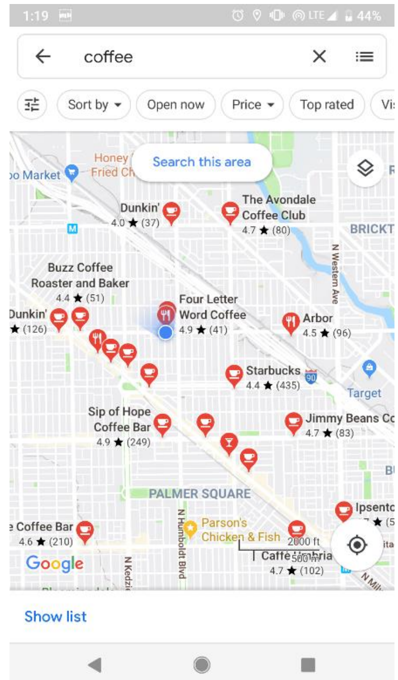

Figure 3.5: Teardrop icons within Google Maps.

<u>Points of Interest</u>

Because mobile maps situate users in the map using GPS and point representations, they commonly support wayfinding and other map use tasks that merit finding ***points of interest*** near to a user. Accordingly, POIs were represented as frequently (83%; 30/36) as the user’s location across the sample. As introduced in Section 3.2.1, POIs typically draw from point data, a convenient data type for storing information that can be displayed without generalization at varying zoom levels and subsequent information densities. Points also typically are the output of geocoding and reverse geocoding and the bounds of routing, producing a single latitude/longitude point coordinate or a pair of origin and destination points, respectively.

Of the sampled apps that represented POIs in the map, 33% (10/30) did so using a ‘teardrop’ icon, another icon style popularized by *Google Maps* and rapidly becoming convention (Figure 3.5). Teardrops have two advantages to other frame shapes for representing POIs: they have a bottom carrot that unambiguously demarcates the location of the POI and also have a compact, circular dead space above the carrot that can hold an iconic silhouette to encode information about the type of POI feature (e.g., school versus museum). Like other point symbols, teardrops also can be colored to depict higher-level categories of information (e.g., natural versus constructed POIs in green versus black). However, use of teardrops can result in visual clutter on mobile maps when the number of POIs is high, and they also place focus on reference mapping and wayfinding versus other potential uses of mobile maps.

Regions of Interest

In addition to displaying points of interest, mobile maps occasionally encode ***regions of interest*** (***ROI***) in the map. When coding for ROIs in mobile maps, I looked for the use of polygons or other non-point data types. Polygons are a common source of cartographic data, but as discussed in Section 3.2.1, only 33% of the sampled mobile maps utilized polygons in their design, all of which used them to represent administrative ROIs (again 33%; 12/36) instead of enumeration boundaries for thematic maps.

Representation strategies for ROIs varied considerably across the sampled mobile maps. For example, *Snapchat* displays regions of high activity using a single heatmap shaded surface (see Figure 3.8) while *Zomato* enables the user to draw interactively the boundaries of a ROI for a geographic filter (Figure 3.6). The most common (41%; 5/12) ROI representation solution across the sampled mobile maps was a single vector outline of the region, usually presented after the ROI was queried. For example, if "Mission" is searched within *Google Maps*, the boundary of the Mission District in San Francisco is displayed with a thin red outline. A similar representation solution is utilized when searching for a region in *Trulia*, *Zillow*, *Citizen*, and *Google Earth*.

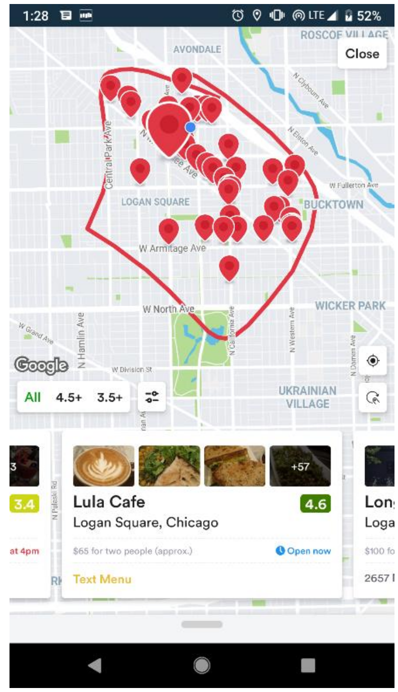

Figure 3.6: The user can draw a custom ROI to filter in Zomato.

The inclusion of non-administrative, ROI boundaries within a mobile map remains an area for further exploration of which kinds of geographic data are appropriate for mobile maps. *Trulia* provides one potentially innovative solution through its "local info" feature (Figure 3.7), where users can overlay a wide variety of information such as census tract statistics, traffic density, and the probability of natural disasters over a basemap depicting available homes to help influence their decision. Overall, the emphasis on POIs and ROIs over other types of polygon representation suggests the primary use of mobile maps for reference mapping rather than thematic mapping, another departure from print and desktop-bound map design. Accordingly, *thematic* mobile map representation remains an open research question (Roth 2019).

Other Users

The ubiquitous connectivity combined with the market saturation of smartphones means that it is now possible for mobile maps to depict not just data and the location of the user as the mobile map is used, but to also include information about other users as they engage with the same mobile mapping app. The inclusion of ***other users*** refers to the representation of either individuals or aggregation of other users' activity within the mobile map.

Figure 3.7: Example of census tract data displaying the median age of residents of the *tract being utilized by* Trulia *for decision making.*

Of the sampled mobile maps, 44% (16/36) represented the location of other users on the map. The depiction of other users in the sampled mobile maps was highly variable, resulting in no identifiable patterns or trends in visual design solutions for representing the other users. Instead, there were some potential emerging practices for treating the potentially sensitive location of other users. Some apps depicted the locations of others in real-time, but otherwise hid any identifying information (*Waze*, *Uber*, *Lyft*).

It also was common for some apps to include the ratings and reviews of other users to allow for communication about a location, commonly for business reviews, but not map the user's location itself (*Google Maps*, *Zomato*, *Fishbrain*). Other apps aggregated location information for other users to create new data layers within the mobile mapping app, such as the creation of *Snapchat's* heatmap to generate ROI clusters (Figure 3.8), or *Google Maps'* traffic feature that aggregates the location and speed of other users to generate areas of traffic in the map. As the potential for including other users in mobile maps expands, it creates new avenues to explore data privacy ethics, especially mobility data, and creates additional questions about what it means to share personal data, as well as new visualization problems as mobile map developers explore additional ways using volunteered geographic information to create additional functionality for individual users.

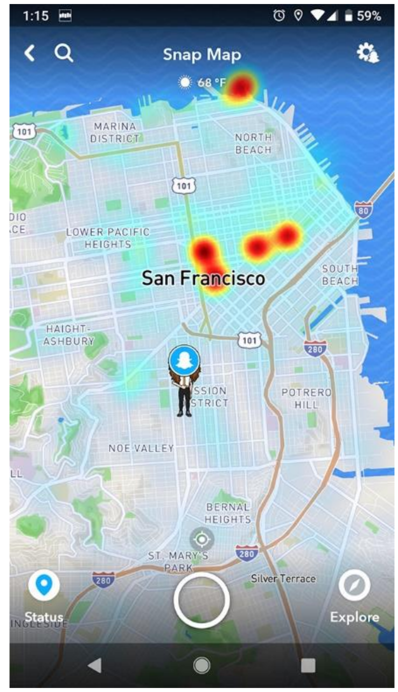

Figure 3.8: Heatmap depicting user activity hotspots in Snapchat.

3.3.2 Basemaps

One of the most influential components on the look and feel of a mobile map is the basemap. The ***basemap*** in a mobile mapping context is the background map that contains the reference material on which additional data layers are overlaid. Basemaps for mobile maps often are created through a mobile mapping SDK (software development kit) and served as either raster or vector tiles to speed loading times and conserve data, as often only a small set of tiles are needed based on the user’s location (Peterson 2011). While I did not have a specific code for basemap provider, it was evident that Google and Mapbox were the two most common tileset sources across the sampled mobile maps. In future research, it would be informative to code for the basemap provider and even a specific basemap source.

Default Basemap

Of the sampled mobile maps, the vast majority, 81% (29/36), used a road map as their default basemap. A ***road*** basemap, often labeled as the ‘street map’, is a tileset emphasizing transportation information useful for navigation. Interestingly, a road basemap often was the default even when the mobile map did not provide a routing service, suggesting it is the conventional basemap reference used for interpreting overlay information. Road basemaps generally are more useful for urban applications than non-urban areas with sparse or incomplete road networks, potentially also suggesting that contemporary mobile map design bends towards an urban market, a trend further reinforced by improved network capabilities and greater density of POIs and ROIs.

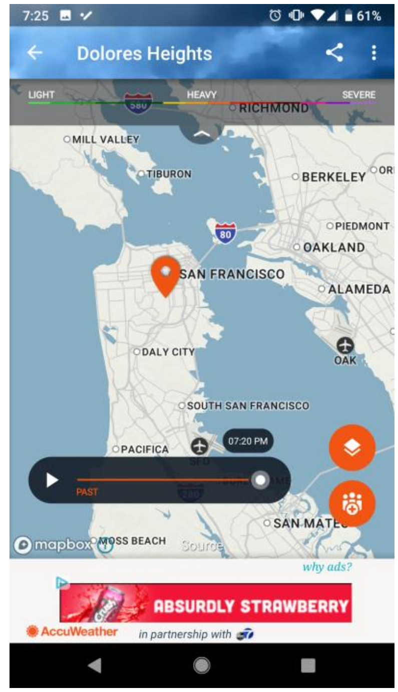

Figure 3.9: Road basemap in AccuWeather.

Of the remaining seven mobile maps not defaulting to a road basemap, two default to a satellite map, two to terrain, and three to custom basemaps designed specifically for the app (Table 3.4). The three apps with custom basemaps all focused on gaming, again reinforcing the importance of representation design for promoting playfulness and engagement: *Pokémon Go*, *Wizards Unite*, and *Gametime.* Accordingly, mobile maps using the standard road basemap provided through a service such as the Google Maps SDK are missing an important branding and marketing opportunity to tailor the basemap to intended purpose of the mobile map.

Table 3.4: Summary of default basemap styles

Default Basemap	**Count**	**%**
Roads	30	83.3%
Other	3	8.3%
Terrain	2	5.6%
Satellite	1	2.8%

Basemap Color Palette

Beyond the type of default basemap, I also coded for brightness and color palette. Regarding brightness, a basemap that is ***light*** (has primarily light colors with the most dominant color being white or pastel) versus ***dark*** (primarily dark colors where the most dominant color is black or otherwise very dark) generally uses more energy, impacting the battery life of OLED screens as well as increasing user eye strain, particularly for nighttime use. Across the sampled mobile maps, 91% (33/36) had a light colored basemap option. In contrast, only 25% (9/36) of the sampled mobile maps had a dark colored basemap, indicating that this option is much less common despite the important energy savings on mobile battery life (Figure 3.10). Six (17%; 6/36) had the ability to toggle between both light and dark (an application of the overlay operator), often supporting a daytime versus nighttime mode. If a basemap is not utilized for its stylistic congruities with the rest of the mobile app, a best practice would be to allow the user to switch between the two options to save battery and reduce eye fatigue.

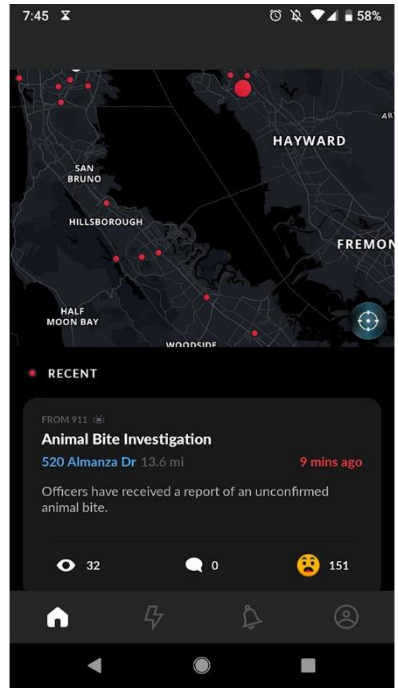

Figure 3.10: The dark and highly stylized basemap in Citizen.

3.3.3 Map Views

The third category of Representation Codes covers additional aspects of the default map perspectives that generally falls under projections, scale, and layout in traditional cartographic representation. These Map View codes include the mobile map's default orientation, default loading view, projection, size, ability to change on rotation, and the default scale of the map.

Figure 3.11: User forward default map orientation during a Totodile community day event in Pokémon Go..

<u>Default Orientation</u>

The orientation of a map is a powerful design tool in a cartographer's toolkit, framing the map context and encouraging a particular interpretation of the landscape. In my coding, the ***default orientation*** describes the directionality of the mobile map on first load. A ***north*** default orientation describes maps with 'up' as due north, contrasted with a ***user forward*** default with the map instead facing the direction the user is looking at that moment. While a north default is convention in print and desktop mapping, a user forward default accounts for the user's mobility in the landscape and improves wayfinding given a switch from cardinal directions (west, east) to embodied directions (left, right) (Klippel et al. 2005). However, across the sampled mobile maps, 92% (33/36) had a northwards default orientation while only 8% (3/33) had a user forward orientation. This was an unexpected finding given the literature on wayfinding and egocentric design. However, the developing convention towards creating north default maps has been reinforced by Google's decision at the time of this writing to hide default compass functionality in their SDK, greatly reducing the likelihood of mobile maps that are user forward by default using Google basemaps and services**.**

Two of the three mobile maps with a user forward default again were for gaming: *Pokémon Go* and *Wizards Unite*. As described in Section 3.3.1, the user is represented as an avatar walking around the mobile map environment in real-time. In these circumstances, the user forward orientation has the effect of embedding the user in the mobile map, enhancing the playfulness of the mobile mapping app (Figure 3.11). The third mobile mapping app with a user forward default was the ticket marketplace *Gametime*. When a ticket is selected from the app, the user is presented with a viewshed of the stadium from the selected seat. Again, this is a useful and task-relevant presentation of a user facing orientation, and suggests further experimentation with non-northwards defaults for mobile maps other than games.

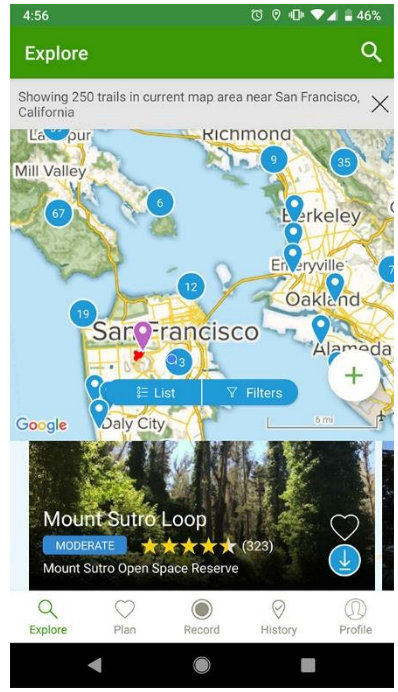

Figure 3.12: Default loading screen of All Trails. *The app is centered on one of the closest trails to the user and gives an overview of available trails in the region.*

Default Loading View

Beyond the default orientation, a mobile map also may or may not center upon the user's location by default. An ***egocentric*** default automatically centers the map on the location of the user. Across the sampled mobile maps, 64% (23/36) have an egocentric default loading view. As discussed in Section 3.3.1, an additional seven mobile maps symbolized the user's location, but did not center the map on the user. For example, *All Trails* (Figure 3.12) loads the map centered on the greater region the user is in, but the location of the user remains encoded as a blue dot with the nearest hike highlighted in a proximity search. The decision to make the user the central point of the map speaks to the overall intention of the map. Ideally, maps that are meant for the user to explore their immediate, neighborhood-level surroundings would load centered on the user more often than those there the intention is to travel and explore a broader region, such as in the case of *All Trails*.

Dimensionality

Traditionally, cartography described the process of projecting a three-dimensional globe onto a two-dimensional map surface. Given the advancement in mobile GPUs and CPUs, smartphones now can process elevation and subsurface data as the user moves through the three-dimensional landscape in real-time. Accordingly, I coded for the ability of smartphones to represent data in both two and three dimensions. I considered the mobile map ***2D*** when presented in a planimetric, top-down perspective, and ***3D*** when presented in an oblique, side-view perspective.

Across the sampled mobile maps, 94% (34/36) included a 2D perspective. The two outlier maps that did not support a 2D perspective again were *Pokémon Go* and *Wizards Unite*. While many spatialized games include overview locator maps that represent the entire playing space (Thorn 2018), it is possible that these were excluded in the gaming apps because the overview map of the game would encompass the entire globe.

Notably, half of the sampled mobile maps (50%; 18/36) supported a 3D view, an arguably much higher rate than found in print or desktop-bound maps. Presenting data in three dimensions can be an enriching and engaging means of interacting with a landscape, such as in the case of *Google Earth.* As exemplified in Figure 3.13, *Google Earth* utilized a ‘birds eye view’ of the city, encouraging open exploration of the landscape by its users and utilizing satellite imagery to create the feeling of really being in a place. Many other mobile maps utilize 3D building footprints as available in the *Google Maps* SDK. The 3D perspective is accessed by swiping the map upward with two fingers to change the camera view, ‘tilting’ the map to reveal extruded building footprints that give the user the feeling of being embedded in the landscape (Google). Unlike in *Google Earth*, the Maps SDK does not extrude satellite imagery. While 3D views have considerable potential for user engagement, altering how they experience places, 3D also drains battery and requires higher data volume and processing, especially on older devices (as explored in Section 2.2.5), and thus should be used intentionally.

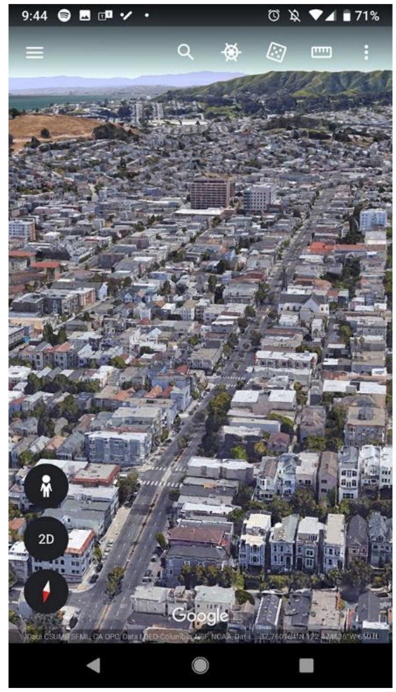

Figure 3.13: A 3D view of the Mission District in San Francisco looking facing south in Google Earth.

Map Size

Section 2.2.3 reviewed the variable screen sizes found on smartphones. However, the screen real-estate used for the map also can vary among apps, further complicating the constraints placed on representation design for mobile maps. ***Map size*** describes the percentage of the screen the map covers on the default loading of the mobile app.

Table 3.5: Summary of the sizes of sampled mobile maps compared to overall screen real-estate.

Map Size	**Count**	**%**
100%	17	47.2%
75%	9	25.0%
50%	6	16.7%
25%	3	8.3%
Less than 25%	1	2.8%

Across the sampled mobile maps, the majority (47%, 17/36) covered either the entire screen or close to the entire screen. Generally, the map covered 50% of more of the screen (32/36; 89%; Table 3.5). The only mobile map that by default covered less than 25% of the screen was *Facebook.* In many mobile maps, it was possible to adjust the overall size of the map compared to other information context using a pull-up or pull-down motion, an explicitly mobile example of the arrange operator discussed in Section 3.4.1. Providing users with interactive functionality to adjust the map size is one important way to overcome the constraints of a small screen size on smartphones.

<u>Change on Rotation</u>

Beyond map size, smartphones pose an additional layout challenge when rotating the handheld device. Many non-mapping mobile applications respond between horizontal and vertical layouts when rotating the device. ***Change on rotation*** describes a mobile map that similarly changes the aspect ratio and adjusts its layout based on the handheld rotation of the device.

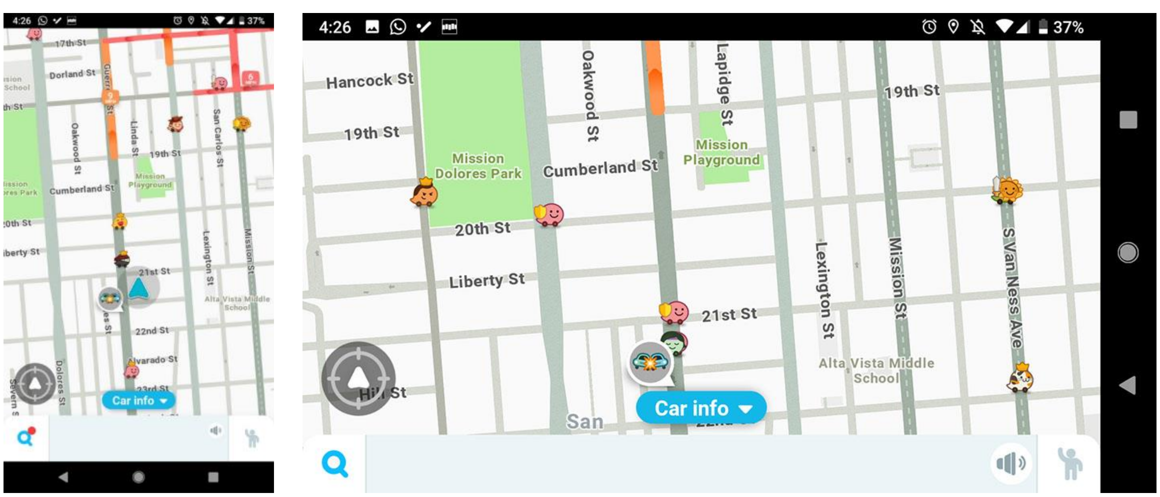

Figure 3.14: Example of how the Waze layout changes on rotation.

Table 3.6: Summary of the default scale of sampled apps

Default Scale	Count	%
Neighborhood	20	55.6%
City	7	19.4%
Regional	5	13.9%
Country	2	5.6%
Global	1	2.8%
Other: Stadium	1	2.8%

Only 22% (8/36) of the sampled mobile maps had the ability to change their layout on rotation. As illustrated in Figure 3.14, changing the layout gives users additional left and right context that might be useful for turning when wayfinding or identifying offscreen geographic features. Changing the layout of the mobile map on rotation also can be useful when the user accesses the smartphone from somewhere other than their hand (for example, an armband while exercising) and would want additional choices based on altered viewing angles.

Default Scale

Finally, the ***default scale*** of a mobile map describes the scale at which the map loads by default. Maps with a *small* cartographic scale have a continental to global coverage, while maps with a *large* cartographic scale have a city or neighborhood coverage. In mobile and web mapping, scale is often understood in terms of *zoom level*, where the higher the zoom level number, the larger the scale of the map (i.e., zoomed in) (Peterson 2011). The entire earth is visible at zoom level 1, while only a few blocks or a single neighborhood are visible at zoom level 20.

While the zoom level can be changed interactively by the user (see Section 3.4), the default scale offers insight into the intended purpose of the mobile map and provides an affordance to the user about how to make use of the mobile map. For example, 55% (20/36) of the sampled mobile maps loaded by default presenting the neighborhood around the user. This clues the user in that the map is most useful locally. Only one of the sampled apps loaded the map at a global scale: *Google Earth.* Accordingly, *Google Earth* invites the user to explore places they have never been, all over the world. Generally, the default map scale was at a city or neighborhood level (75%; 27/36), again emphasizing the user's current location and reference mapping. Table 3.6 provides an overview of the default scales of the sampled mobile maps.

3.3.4 Map Elements

The final set of codes in the Representation Design category cover map elements that aid in the reading and comprehension of the mobile map design. ***Map elements*** are the non-data building blocks of cartographic communication (Slocum et al. 2009). Here, I examine map elements that that are common in traditional and mobile maps alike but may have different application and use for the mobile context. Specifically, I examined indication of orientation, indication of scale, and legend, but did not assess other map elements described by Slocum et al. (2009) that are explicitly for printed maps (e.g., neatlines, titles).

Indications of Orientation

The ***indication of orientation*** refers to the presence of a visual annotation of north to orient the user to the cardinal directions. North arrows and compass roses traditionally are recommended for large scale maps where north remains in a consistent direction across the map and an overlaid graticule is recommended for small scale maps where north changes across the map. North arrows can be particularly helpful when the default view of the map is adjusted from north-up (Figure 3.15). Eleven (31%; 11/36) of the sampled mobile maps included either a north arrow or a compass rose.

Several of the north arrow and compass rose icons had the additional functionality of reorienting the mobile map. If the orientation of the map had been changed, tapping the orientation icon would make the map readjust to north-up. Explored further in Section 3.4.1, many maps constrained the ability to adjust the orientation. When orientation adjustment is constrained, the convention is that the mobile map is orientated northwards and the need for a north arrow is reduced. It was common the north arrow or compass roses only to appear after reorientation, serving as an ‘undo’ or ‘back’ metaphor. This latter “compass on change” convention originates from the Google Maps SDK for Android, providing yet another example how several companies are driving conventions. I did not observe an example of a graticule in the sample given the large scale focus of most mobile mapping applications, although many maps had an implicit graticule as basemap tiles loaded in a Web Mercator projection.

Figure 3.15: A detailed compass helps users navigate with an egocentric view in Wizards Unite.

Indications of Scale

As described in Section 3.3.3, map scale describes the relationship between measurements on the map and measurements in the real world. Slocum et al. (2009) describes three ***indications of scale*** to apprise the map use of this relationship: representative fractions, verbal scales, and scale bars. Across the sampled mobile maps, only 11% (4/36) included an indication of scale. Accordingly, indications of scale represent an area for design improvements in mobile maps, particularly given how few mobile maps in the sample had routing services that would otherwise replace an indication of scale during wayfinding.

Figure 3.16: A storm over the midwestern United States as depicted in The Weather Channel.

<u>Legend</u>

Finally, the ***legend*** is the map element that defines all the thematic symbols on the map. Only 11% (4/36) of the sampled mobile maps include a legend. Legends commonly are included on print and desktop-bound maps, particularly for thematic maps. While low, it is perhaps unsurprising that few mobile maps include legends due to the limited screen real estate and the focus on reference over thematic mapping. One of the likely reasons for the lack of legends included in mobile maps is the symbol standardization of common map features such as points of interest. As observed in Section 3.3.1, the vast majority of POIs were coded using highly-iconic teardrop symbols. When using a standardized symbol style, the map designer likely assumes a legend is redundant. Exploration into actual user interpretation of common mobile map symbols would be a rich area of further research.

Apps that did include a legend displayed thematic data encoded on an ordinal or interval scale (e.g., weather or census data). However, even these presented minimal legend designs, such as *The Weather Channel* legend showing multiple color ramps without providing specific numerical values (Figure 3.16). Future research is needed to understand the negative impacts of excluding legends from many mobile maps, particularly to promote mobile maps that are inclusive and accessible.

3.4 Mobile Map Interaction Design

Mobile maps support new forms of digital interactivity uncommon to other mapping media due to touch-based interaction and unique feedback mechanisms. Mobile maps in some ways return to the natural interactivity of paper maps because the smartphone must be held to be interacted with, bringing the user closer to the map through their interaction (Roth 2012). I applied Roth's (2013b) interaction operators to mobile maps to understand how the interactive functionality of mobile maps differs from print and desktop-bound interactive maps. ***Operators*** are the generic actions a user can perform to manipulate the map representation. Roth further separates the cartographic interaction operators into two categories: *work operators* and *enabling operators*. ***Work Operators*** accomplish desired user objectives, while ***enabling operators*** help to prepare for or clean up from work operators. Finally, I also coded for the unique feedback mechanisms enabled by the mobile medium, specifically haptic feedback and unique uses of sound.

Table 3.7: Summary of interaction operators and unique interaction mechanisms

Category	Code	Definition	Count	%
Work Operators	*Pan*	The user can change the geographic center of the map	33	91.7%
	Zoom	The user can change the scale of the map	36	100.0%
	Semantic Zoom	The user can change scales to adjust information complexity	33	91.7%
	Rotate	The user can change the orientation of the map	22	61.1%
	Overlay	The user can adjust (i.e., toggle visibility) of overlaying map features	18	50.0%
	Overlay - Bicycling	The map includes bicycling information as an overlay	1	2.8%
	Overlay - Transit	The map includes roads and transportation information as an overlay	1	2.8%
	Underlay - Roads	The basemap includes roads and transportation information	30	83.3%
	Underlay - Satellite	The basemap includes satellite imagery	15	41.7%
	Underlay - Terrain	The basemap includes terrain	7	19.4%
	Filter	The user can identify map features meeting certain criteria	18	50.0%
	Search	The user can identify a particular location or map feature of interest	26	72.2%
	Calculate	The user can derive new information about map features of interest	8	22.2%
	Retrieve	The user can request specific details about map features	34	94.4%
	Arrange	The user can manipulate the layout of views	19	52.8%
	Sequence	The user can generate an ordered set of maps	6	16.7%
	Reproject	The user can change the map projection	17	47.2%
	Reexpress	The user can change the visual cartographic representation	0	0.0%
	Resymbolize	The user can change design parameters of map features	1	2.8%
Enabling Operators	*Import*	The user can load geographic information or a previously generated map	3	8.3%
	Export - Share	The map allows the user to share their map, either over social media or otherwise	27	75.0%
	Save	The user can store the geographic information of map	10	27.8%
	Edit	The user can manipulate geographic information underlying the map	9	25.0%
	Annotate	The user can add graphic markings and/or textual notes to map	12	33.3%
Unique Interactivity	*Haptic Feedback*	The map responds to haptic feedback or vibration	6	16.7%
	Sound - Language Prompts	The map responds to audio prompts using language sounds	5	13.9%
	Sound - Non-Language Prompts	The map responds to audio prompts using non-language sounds	8	22.2%

3.4.1 Work Operators

Pan

Pan describes the ability to adjust the geographic center of the mobile map and make visible portions of that map that previously were hidden beyond the bounds of the smartphone screen. The ability to *pan* is essential for mobile maps because of the smartphone's small screen and limited aspect ratio. Panning typically is achieved on mobile maps through a single finger 'tap and drag'. In many mobile maps, it also was possible to recenter the map on the user's location through a separate 'crosshairs' search button. Pan was the third most frequently employed work operator, with 92% (33/36) of the sampled mobile maps allowing users to change the center of the map.

The three mobile maps that did not allow the user to pan were *Samsung Health, Pokémon Go,* and *Wizards Unite.* The limited use of pan in game apps acts as a function of the apps constraining how much of the real world is available for the players at any given time. It is not useful, and potentially frustrating, for players explore game spaces and events that are currently inaccessible; instead, players need to unlock these incomplete worlds as part of gameplay (Thorn 2018). In the case of *Samsung Health*, the inability to change the map view was a feature I found frustrating as a user while running with the app, making it difficult to plan or see what was ahead.

I did not record if the map design constrained the amount of panning, and by extension the amount of map made available to the user through the pan operator. Unlimited panning functionality means it is possible for the user to explore the entire world using a mobile map regardless of the geographic focus of the map and the availability of map data outside of specific areas. For example, the app *Citizen* constrains zoom level (see below), but not panning, allowing the user to navigate to areas where the app does not operate. At the time of writing, *Citizen* only operates in New York City, the San Francisco Bay Area, Baltimore, Los Angeles and Philadelphia, despite unconstrained panning outside of these regions.

<u>Zoom</u>

Zoom describes a user-driven change in scale and/or the resolution of the map. Zoom typically is achieved on mobile maps using a 'pinching' motion where the user moves two fingers together on the map to reduce the scale, or moves two fingers apart to increase it, a metaphor from the 'rubber band zoom' found in web maps and desktop GIS (Harrower and Sheesley 2005). Of the sampled mobile maps, 100% (36/36) contained the ability to adjust the map scale, making zoom the most common interaction operator in the sample and suggesting zoom is ubiquitous to mobile mapping regarding of the map purpose.

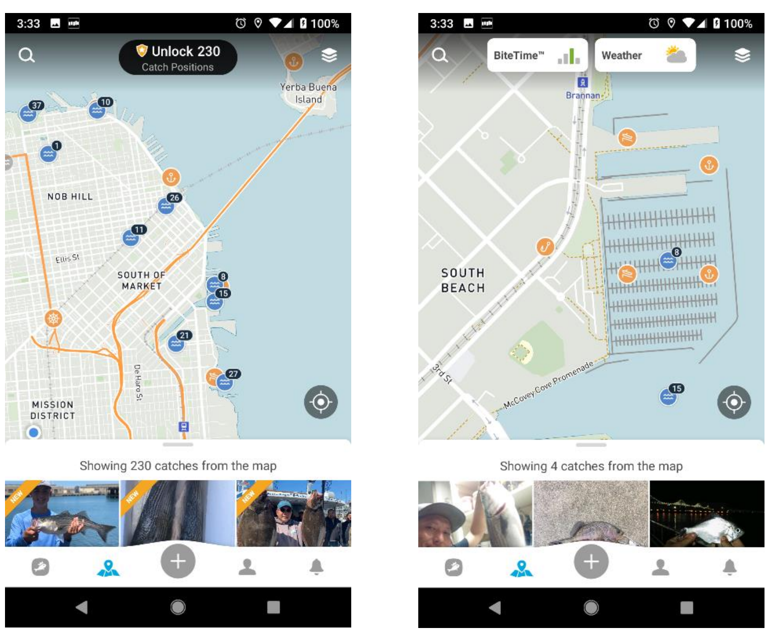

Figure 3.17: Basemap detail increasing from the smaller scale map (left) to the larger scale (right) through the utilization of semantic zoom in Fishbrain.

In addition to the ability to adjust the map scale, 92% (33/36) of the sampled mobile maps also adjusted the information complexity of the map while zooming. ***Semantic zoom*** refers to adjustment of map features and labels to best display across scales, providing scale-dependent information arrangements (Tanaka and Ichikawa 1988). Figure 3.17 provides an example of semantic zoom in *Fishbrain.* In the first map, the user can see most of eastern San Francisco with only neighborhoods and some roads labeled. As the user zooms into the second map, points and labels are added for individual piers, walking paths, and transit locations, providing much greater information complexity in the map without relying on other interaction operators like retrieve. The apps that did not feature sematic zoom included: *Pokémon Go, Wizards Unite,* and *Gametime.* For these three mobile maps, the resolution of the map changed as users zoomed in and out, but information was not added or removed from the map.

The prevalence of pan and zoom in mobile maps bucks the common web cartography recommendation to constrain the scale and extent of the map to avoid the user from 'getting lost' in the map, as excessive pans and zooms can indicate confusion and disorientation (Roth 2013a; Roth and MacEachren 2016). Unlimited panning and zooming also has financial implications, as companies that provide basemap tilesets (e.g., Mapbox) move to using a per-tileview pricing model rather than flat subscription rates. An unconstrained map view results in many accidental tile views that are potentially irrelevant based on the user's location.

Rotate

Rotate describes the ability to change the default viewing orientation, typically from north-up to another view as discussed in Section 3.3.3. Rotate helps user's generate an egocentric view ("what is X in front me?") and adjust the layout of map features that fit awkwardly on a tall, narrow screen. Typically, rotate is achieved on mobile maps by a 'two-finger twist' on the screen of the smartphone, with one finger stationary used as an anchor and the second finger moving as the spindle. Within the sampled mobile maps, 61% (22/36) allowed the user to rotate the map.

Roth (2013a) initially grouped *rotate* with the *reproject* operator, as there were few examples of touch-based, 'two-finger twist' rotation likely given the relative infancy of mobile maps at the time of the study (2010). Inarguably, rotate is now a core work operator in mobile maps given the importance of generating egocentric views while navigating in the landscape, and thus is treated as its own operator in this analysis. Further, rotate is an embodied interaction on many mobile maps, pointing to new and unique input mechanisms with mobile, as rotating one's body often rotates the viewshed of the blue dot icon. Embodied rotation can be an incredibly useful for completing wayfinding tasks, allowing the user to quickly check if they are walking in the intended direction.

Overlay

Overlay describes adjustment to the feature types included on a map, adding and removing context. Unlike traditional printed maps, where the cartographer intentionally selects and generalizes the data layers included within the visual hierarchy, interactive cartography has made it possible for cartographers to add as many data layers as desired to an application, adding and removing data at will. Across the sampled mobile maps, 50% (18/36) allowed the user to overlay additional datasets onto the map.

Overlay was implemented in two primary ways within the sample. First, the more common solution was toggling additional data layers or different basemaps on and off using an off-map menu (Figure 3.18). The most common underlays (the ability to change the basemap using the overlay operator) in the sampled mobile maps were roads (83%; 30/36) and satellite layers (42%; 15/36). Notability, only *Google Maps* allowed the user to overlay linear features such as transit and bicycling information, with all other non-basemap overlays point or polygon features. Second, overlay occasionally was combined with semantic zoom, with the data layers adjusted depending on zoom level. For example, in the *Snapchat* map, once the user zooms to zoom level 14, the mobile map shifts from a roads basemap to a satellite basemap

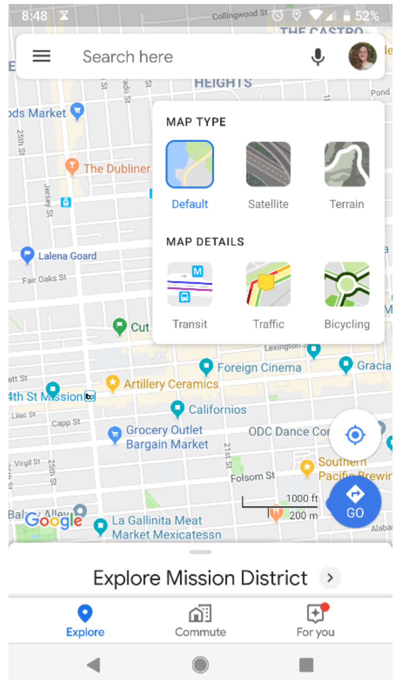

Figure 3.18: Overlays and underlays available in Google Maps.

Filter

Filtering highlights or removes map feature(s) that meet user specified criteria. In many ways, the promise of mobile maps is personalization. These maps contain huge amounts of information, both seen and unseen, and the user is empowered to query for the information most useful to them. In addition to overlay, one of the easiest ways for users to customize information on the mobile map is through filter. However, only half (50%; 18/36) of the sampled mobile maps enabled filtering.

Notably, all mobile maps that implemented filtering also featured points of interest. It often was necessary to filter POIs due to the large volume of potential POIs for display on the map. One of the main assumptions inherent to many mobile maps is that all the data is not visualized at once, and instead it is up to the user to either overlay or filter task-relevant data. Figure 3.19 provides an example filter query in the mobile map *Zillow*, which allows users to filter prospective homes with a great deal of granularity, customizing the map to show only the most relevant results. Occasionally, users were provided with the option to filter geographically by directly drawing the area they would like to query on the basemap, a useful and interactive solution for proximity filter that does not rely on LBS.

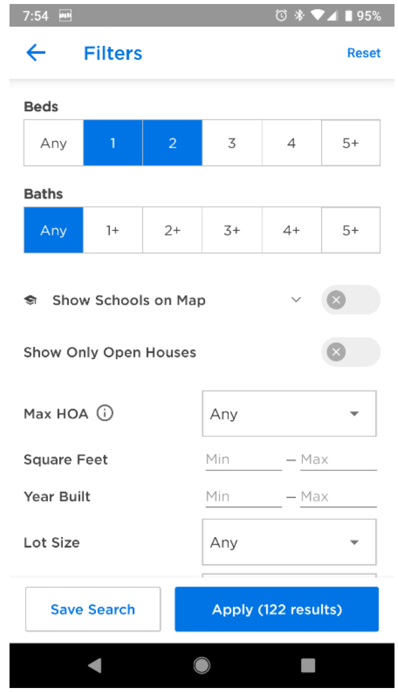

Figure 3.19: Filtering options in Zillow.

Search

Search describes isolation of a map feature or a category of map features using a single query. Search is yet another way for users to customize the mobile map, but unlike overlay and filter that provide visual affordances about available data layers and schema, search requires that the user knows what they are seeking before interacting. The majority of sampled mobile maps (72%; 26/36) allowed users to search the mobile map. While often employed in combination, search versus filter tends to demarcate simple, general user apps versus exploratory, expert user apps (Roth and MacEachren 2016), perhaps an expected finding given the sample only included popular and free mobile maps downloaded by many users.

Search typically was achieved through a form fill-in text query. Text-based search often included auto-populated suggestions as the user types to speed keying and reduce errors (e.g., Figure 3.20). Accordingly, search also presents one opportunity to use the unique input and feedback mechanisms of the mobile device, specifically voice recognition. As discussed above, it also was possible in many mobile maps to search for the user's location using a 'crosshairs' search button, with the map then panning to recenter on this location.

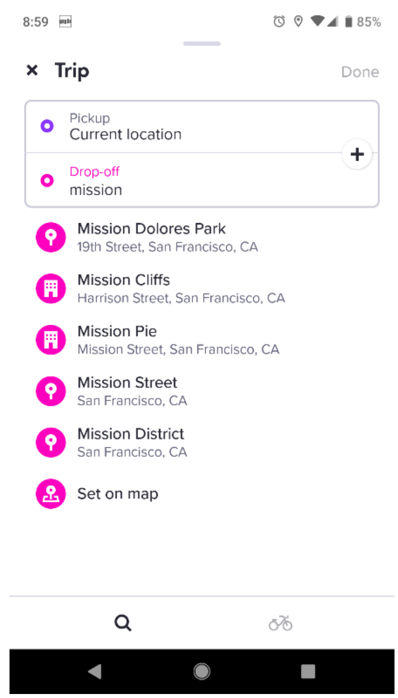

Figure 3.20: Lyft *autocompletes search queries with nearby matches. Notably, the app has created point locations for line and polygon features.*

<u>Calculate</u>

Calculate as an interaction operator describes the ability to perform user-calibrated computational tasks such as calculating the distance between two points or the amount of time it would take to travel from one location to another. The ability to perform calculations interactively is particularly useful for completing wayfinding activities such as determining how much time a trip will take in advance. Calculate also can be useful in its ability to provide an alternative, verbal scale (i.e., "place A and B are 20 minutes apart by bicycle"). Calculate was relatively rare among the sampled mobile maps, appearing in 19% (7/36) of sample.

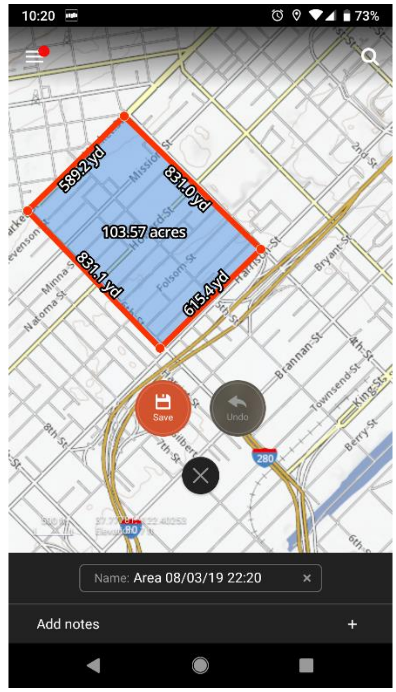

Figure 3.21: Calculating the area of a polygon in onX Hunt.

Five mobile maps used calculate to perform routing tasks based on user interactions in addition to or instead of the GPS alone (see Section 3.2.2). One mobile map, *onX Hunt*, allowed the user to annotate the map and, through that annotation, provided calculations about the user's annotations. For example, the user can draw a polygon and *onX Hunt* calculates both the area of the polygon and the length of each polygon side, as seen in Figure 3.21. Other mobile maps that included calculate outside of wayfinding activities also included the ability to calculate the distance between two points. In wayfinding, the assumptions involved in the calculation are often obscured from the user, and map designers have a potential opportunity to open those assumptions up to users through visual affordances and novel interface designs. For example, when giving walking directions, it is often obscured from the user how walking speed is calculated. If users were provided ways of manually adjusting this speed, perhaps it would better serve users whose travel speed deviates from the norm, such as those with disabilities or traveling with children.

<u>Retrieve</u>

Retrieve describes actions providing the user with additional information about features of interest on the map. Retrieve is the third component of the Visual Information-Seeking Mantra of overview first, zoom and filter, and details on demand, a design mantra often evoked for the context of exploratory geovisualization (Shneiderman 1996). However, retrieve may be even more important to mobile maps given the constraints of small screens and high data complexity, making it difficult to visualize all information at once on the map. The vast majority (94%; 34/36) of the sampled mobile maps allowed user to retrieve additional information about map features through the execution of the retrieve function, making it one of the most common operators along with panning and zooming.

Commonly, retrieve was achieved by manually ‘tapping’ a POI on the screen, after which the map would subsequently populate with additional information about the selected POI. The three apps that did not allow users to retrieve additional information about objects on the map were *Samsung Health* and *OfferUp.* Both apps have highly constrained interactivity, and neither allowed the user to query the map, making it clear that “information seeking” was not a key component of map function in these examples. It is clear from the prevalence of the operator that retrieve is an essential part of mobile map functionality, and instead of asking should retrieve be used, mobile map designers should instead always be asking themselves what information is most useful to be displayed when the user expectedly requests additional details.

<u>Arrange</u>

Arrange allows the user to adjust the map layout, traditionally through manipulation of one map relative to other linked map and non-map visualizations. More than half (53%; 19/36) of the sampled mobile maps allowed the user to arrange linked views, usually through allowing the user to either pull up or pull down descriptive text information or flip through ‘cards’ relating back to each POI on the map. The absence of multiple map views is a missed opportunity in mobile map design, as users would likely benefit from the ability to manipulate a mobile map without losing greater geographic context. Few of the sampled mobile maps provided more than one map at a time, lacking inset or locator maps, likely due to the constraints of the small screen size. *Gametime* is a rare example of a mobile map including multiple map views, but not linking the views (Figure 3.22).

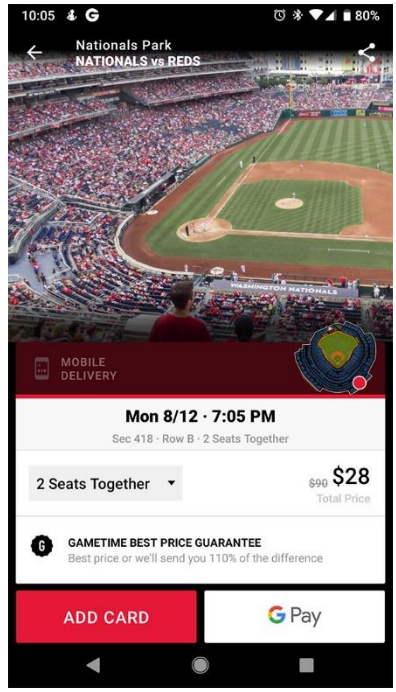

Figure 3.22: Inset and overview view in Gametime.

<u>Sequence</u>

Sequence describes the ability to order and progress through a set of maps. The ability to order and display a set of related maps can be a useful tool for users to understand change through their interaction with the map series. Often the sequence operator is used to animate changes over time. Of the sampled mobile maps, 17% (6/36) allowed the users to sequence a series of maps to complete a task. Both weather apps, *The Weather Channel* and *Accuweather* allowed the user to sequence weather predictions for a day at hour intervals. *Google Maps* also allowed the user to sequence a series of maps for wayfinding purposes, allowing users to step forward and back along a route, where each step represents a turn onto a different road (Figure 3.23). Sequence is a powerful operator for representing events outside of the current map state (either the future or past).

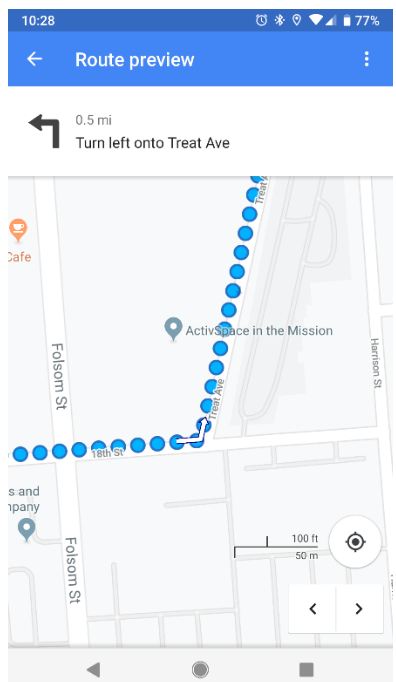

Figure 3.23: Turn by turn directions Google Maps *sequenced using carrot arrows in lower right corner.*

Including the sequence operator would enable mobile map developers to create history and context in the application, a useful feature outside of weather and wayfinding.

Figure 3.24: An example of a 3D view in Capital One.

Reproject

Reproject describes the ability of the user to change the map projection. Maps inherently suffer from distortion. Depending on the overall goals of the map, reprojection can be a useful tool to address these distortions and ensure the overall message of the map, especially at smaller scales. Almost half of the sampled mobile maps (47%; 17/36) allowed the user to reproject the map in some way.

Reproject was most frequently achieved by allowing the user to change the map to a 3D view. Often, such as in the case of the *Capital One* app featured in Figure 3.24, this reprojection added little functionality to the map. Because the vast majority of the sampled mobile maps were mapped using the Web Mercator projection (88%, 32/36), a product of web-based map tile services using this projection by default, projection into a different geographic coordinate system while still using web titles is a great technical hurdle and was not observed in the sample. However, because most of the mobile maps featured were displaying information meant to be viewed at a neighborhood or city level (Section 3.3.3), Web Mercator generally was an appropriate default solution.

Reexpress

Reexpress allows the user to change the kind of map displayed through altering the representation type of the map and/or how the map encodes data. For example, providing the user with the ability to change a proportional symbol map to a choropleth map is an example of reexpress. None of the sampled mobile maps employed the reexpress operator, an absence that is likely explained by few mobile maps displaying complex thematic data that would warrant visual reexpression. One exception is *Trulia*, an app that provides thematic overlays that could be reexpressed into different map types based on the type of data and visual complexity.

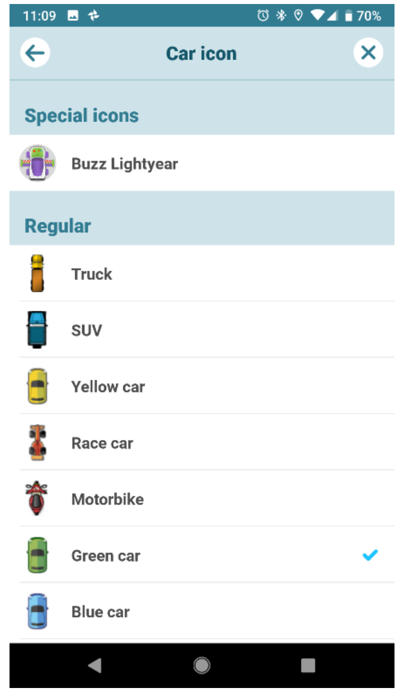

Figure 3.25: Car symbolization options in Waze.

Resymbolize

Resymbolize enables the user to can change the way data is represented on a map without changing the map type. Resymbolize includes changing the classification scheme, class breaks, color scheme, scaling ratios, etc. Only one map sampled, *Waze*, allowed the user to resymbolize any part of the map. Even then, the resymbolization in *Waze* is provided more as a gimmick where users can change how their vehicle is symbolized within the app (see Figure 3.25 for the available symbol options). Resymbolization within a mobile map is an important tool for expanding mobile map utility for a wide variety of users, especially across different cultural contexts and abilities. Its underutilization in mobile mapping is a shortfall of design and an area that mobile map designers should consider moving forward.

That said, it is important to consider any additional data costs on the user that resymbolization would require, or if the conversion takes place on the smartphone, the computing resources required.

3.4.2 Enabling Operators

Import

Import is the action where users can load their own dataset into the map or a previously generated map. Across the sampled mobile maps, only 8% (3/36) allowed users to import their own information. The three maps that allowed this action were *AllTrails, onX Hunt*, and *Google Earth.*

Google Earth on mobile is a small part of a much larger geospatial information system. *Google Earth* predates mobile map use, and one core component of this system is the ability to create and share geospatial data without needing the expertise required of geospatial professionals who use more robust systems like ArcMap or QGIS. It is therefore likely that some of the custom GIS functionality was maintained in the mobile app, such as allowing users to import their own spatial data files as a result of historical expectations rather than forward looking innovation. Import into *Google Earth* is limited to vector files.

onX Hunt and *AllTrails* are similar in that both maps have robust paid features (only the free version of the app was evaluated). Both maps are aimed towards enabling people who need a robust offline mapping platform to take into the wilderness for days at time. In these situations, it is common to allow users to import their own maps into the mobile mapping app that might be more detailed or better suited for their needs than what the platform already has available. It is therefore possible to theorize that *import* might appear with more frequency in paid mapping apps to tailor the map to user interests and needs.

Export / Share

Share refers to the user's ability to send information from the mobile map, on social media or otherwise, to other users, and is a special case of Roth's (2013b) export operator. Share plays an important collaborative role in mobile maps, enabling users to communicate by sharing either information from the mobile map or the entire mobile map view itself for opening on another user's device. Across the sampled mobile maps, 75% (27/36) provided a way to share information from the map with other users.

Share was achieved in a variety of ways, with some apps sending links that opened in a browser, some offered to open in the app if the shared user also had the app installed, and other maps such as *Accuweather* essentially sharing a screenshot of the current map view. Some navigation apps such as *Uber, Lyft,* and *Waze* included the ability to share a link to a map that updates with the sender's location in real time, allowing those with the link to track their current location. According, share serves the dual purpose of supporting collaboration as well as expanding the user base, perhaps the latter explaining the frequency of share in the sampled mobile maps.

Save

Save describes the ability to return to a specific map view generated through previous user actions. Conceptually similar to *export*, *save* speaks to the ability to save a map and continue work in the map or reference it later within the app instead of a single captured a moment in time. In the sample, 28%, (10/36) of the maps provided the user with the ability to save a form of the mobile map. Often, this was achieved by saving searches or filters within the app that can be reopened later. Another common way for users to save a mobile map was through the utilization of bookmarks. Users can manage large number of POIs through bookmarks, making returning to common locations and queries easy. *Google Maps* in particular has made the act of saving a series of POIs in a map particularly easy, featuring a series of customizable lists. As shown in Figure 3.26, that the user can add to and even make their own custom lists, all of which are color-coded on the map.

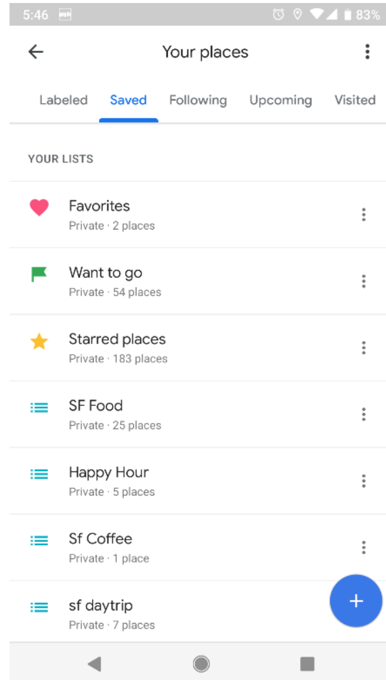

Figure 3.26: Example custom lists saved in Google Maps.

Edit

Edit describes actions that alters the geographic information in the map, thus altering the future representations of the information on the map. Editing can include the ability to add, create, delete, join, or move objects within the map. Across the sampled mobile maps, 9/36 (25%) allowed the user to edit information within the mobile map.

In *Waze* and *Google*, the user can notify Google of potential accidents or construction projects that might impact traffic, creating new icons within the map. In the case of both plant identification apps (*PlantNet* and *PlanetSnap*), the location of a user's identification is added to their personal map when they identify a new plant. In all examples of edit, the user could add information to the map but was never provided a means of removing information from the map. In order to remove geographic data from a public mobile map, a more opaque process must be completed, sometimes using a non-mobile version of the map or even contacting the company that makes the map. Thus, future research is needed to provide mechanisms for deleting information, particularly private or personally-sensitive information.

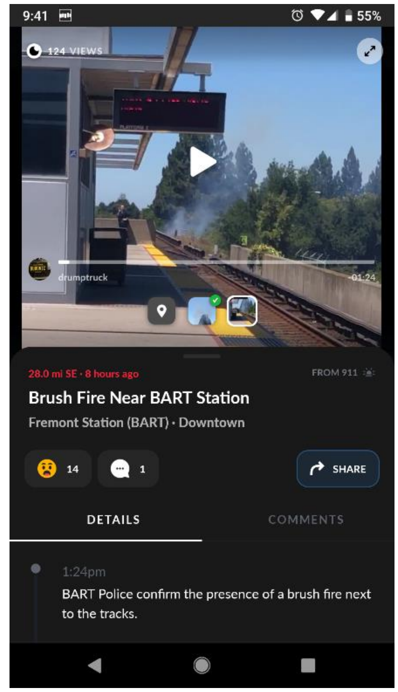

Figure 3.27: User-provided video of a brush fire near a transit station in the app Citizen.

<u>Annotate</u>

Annotate describes the ability of the user to add notes, sketches, and other context atop the map for other users or for themselves. One-third (33%; 12/36) of the sampled mobile maps supported annotation. I considered it annotation if the map provided the user the option to draw on the map, to save places (but not add them) with unique labels, and to write reviews or otherwise add information to preexisting map features. For example, in the app *Citizen*, users can provide video of a crime to the app, so that when other users select the crime they can watch video of the incident (Figure 3.27). In *Google Maps*, it is possible to save addresses with unique names (examples include “Work” or “Landlord’s House”), which the user can then search for within only their app, providing additional utility and saving time.

3.4.3 Unique Interactivity

<u>Haptic Feedback</u>

Haptic feedback is the process of returning information to the user after an interaction through the sense of touch. Haptic environments make visual environments tangible by augmenting, or in rare cases, replacing visual displays with touch. Smartphones are a unique mapping environment in their ability to visualize geographic phenomena using multiple sensory modalities (Fritz and Barner 1999; Griffin 2001). I coded the sampled mobile maps for haptic feedback if the smartphone vibrated in response to a map interaction or updated event. An unintended, but potentially beneficial byproduct of haptic notifications is that because of the mechanisms that allow the smartphone to vibrate, this vibration becomes auditory as well, serving as a sound-based notification in addition to a touch-based one (see below). Haptic feedback was relatively uncommon in the sampled mobile maps, with only 17% (6/36) utilizing the smartphone's vibration capabilities for geographic events.

The sampled mobile maps utilized haptic feedback for a wide range of scenarios and alerts within the map. For example, *Google Maps* vibrates if a user is navigating by foot to alert them that they should turn. Both *Uber* and *Lyft* used vibration to notify the user that their ride is approaching. In *Pokémon Go,* vibration was employed when a new Pokémon appears, alerting the user that they might want to return their attention to the app if they had been using the "Battery Saver" option. Haptic feedback is a powerful took to reinforce in app events, and potentially a helpful force to allow engagement with an app without needing to look at it. However, no standard for haptic feedback mechanisms has emerged, and future research and creative design solutions are needed to better deploy haptic feedback in mobile mapping.

Sound

In addition to haptic feedback, smartphones also come equipped with speakers that empower the device the make use of a third human sense, hearing. Mobile maps can utilize sound in two ways: through providing ***language prompts*** where the user is notified of an event through spoken language, and ***non-language prompts,*** where the user is notified of an event through a sound such as a ‘chirp’ or a ‘ring’.

Of the maps sampled, 14% (5/36) utilized language prompts and 22% (8/36) utilized non-language prompts. Four mobile maps used both: *Waze, Wizards Unite, Google Maps,* and *Find My Kids*. For *Waze* and *Google Maps*, directions were provided verbally, allowing the user to navigate without looking at the smartphone. ‘Beep’ notifications also were used to alert the user of other map changes, but events that were less of a concern than a missed turn. It was common for apps to use sound to accompany push notifications when the smartphone was not actively in use. In this way, sound becomes a device to demand the user’s attention, enabling constant engagement with the smartphone.

CHAPTER 4: WHERE DO WE GO FROM HERE?

The research reported here seeks answers for two questions: how do smartphones enable and constrain design as a mobile mapping platform, and how are mobile maps currently being designed. In this section, I synthesize the intersecting answers of these two questions to understand the ways that mobile map designers can better utilize smartphones as a mapping medium.

4.1 Research Questions

4.1.1 RQ 1: What makes smartphones a unique medium for map design and development?

Generally, smartphones impose two kinds of constraints on map design and use. First, smartphones impact the data services and quality of the data loaded into the map, requiring new solutions to account for limited resources of bandwidth, battery, and processing power. Second, the small size of the smartphone screen and its use in variable mobile conditions requires new visual designs for mobile maps.

Beyond these constraints, smartphones also enable unique opportunities for mobile maps that are not possible on different mapping media. Due to the relatively small size of the smartphone compared to traditional desktop computers and paper maps, the smartphone is mobile and meant to be used both outdoors and indoors. Smartphones also include a variety of sensors opening new capabilities in mobile maps that have not been possible in previous mapping media. Mobile maps, for example, not only position the map user in geographic space but can also sense the speed of the user navigating geographic space. Further, mobile maps locate and orient users amidst real-time data and can support haptic and sonic feedback. Most importantly, smartphones are constantly evolving. Smartphones have undergone major changes in the last decade. Growing screens and shrinking bezels, more powerful batteries and nimble processors, all resulting in devices that can display novel maps and support novel map uses that were not possible 10 years ago.

RQ 1a: What are the constraints imposed by the hardware of the mobile medium on cartographic design?

In the past decade, many of the constraints placed on smartphones largely are assuaged by developments in mobile technology, making these devices small competitors that are replacing traditional desktop computers and home Wi-Fi. The constraint of limited data access through a mobile carrier are alleviated, as all smartphones sampled from 2016 onwards have access to 4G networks whose download and upload speeds in ideal conditions can compete with Wi-Fi networks in data delivery speeds. However, a smartphone's ability to access faster networks and experience subsequent improvements in map and data load times does not mean that users outside of large metropolitan areas with good cellular service coverage networks will experience these improvements. Data conservation in mobile map design was rare, and instead relied on the user to turn conservation methods on in their smartphone's operating system and not within the mobile map. Some of these ill effects could be offset by the ability to provide data caching and offline modes, but generally this functionality was uncommon. Instead, the mobile maps simply did not work in low or no data environments.

Over time, the battery capacity of smartphones sampled more than doubled. This increase in capacity is not reflected in the actual battery life when the smartphone the is in use. The mobile map designs presented in this study negatively impacted battery life and were not optimized to extend or even reach the battery life potential of the smartphone. The battery capacity for mobile map design, and mobile app design more broadly, has been neglected throughout the design process and opens immense opportunities for improvement. In an effort to track their children, parents using *Life360* drain their smartphone battery while the app continuously utilizes sensors, collects their child's location, and reconciles this information with the parent's own location, all of which potentially leaves their children lost without smartphone access if the app fully drains the battery. *Life360* could be optimized to cache routine geographic locations like home, school, and a friend's house to save battery life. Representation decisions also negatively impact battery life. The use of light basemaps over dark, the surprising use of 3D mapping, and the requirement of constant data connectivity for the continued functionality of the mobile map, place an increased burden on the user to optimize the battery life in the operating system and remember an outside power source for the smartphone.

The smartphone screen is the primary way of viewing the mobile map, and over time smartphones have trended towards larger screens. In the sample of phones analyzed, there is an upward limit to how large smartphone manufacturers are willing make a smartphone screen; this limit is about 6 inches diagonal, as screen sizes appeared to be starting to flatten out in the later years of the sample. As screen sizes get larger, there is also a trend towards decreasing bezel size and together they increase the amount of screen space potential for mobile maps. More screen space for mobile maps supports the immersive potential of the smartphone, as the experience of using the smartphone becomes increasingly uncluttered with other features, a portal into an alternative geography.

Other than constraints to map layout and size, the greatest influence the smartphone screen has on mobile map design is the screen technology itself. As screen technology evolves to increase contrast in bright environments, outdoor map use remains difficult. Mobile map design can and should be tied back to screen technology. Developers should try to optimize the design of mobile maps using interaction operators to address visualization challenges created by small and narrow screen sizes. Improved screen pixel density and vibrancy of colors increasingly enable new map representation possibilities, such as responsive design to different viewing environments. In addition to ‘light mode’ and ‘dark mode’, mobile maps meant to be used outside could potentially include an ‘outside’ mode that increases contrast issues within the mobile map and offer a simplified display meant to be viewed and understood quickly.

In the past decade, smartphones have become considerably faster. Smartphone manufactures have greatly increased the number of CPU cores available in phones for processing tasks, and advances in GPU technology have enabled seamless 3D experiences in the mobile mapping space that were previously not widely possible. As processing power increases, mobile map designers can perform increasingly complex analysis at the site of the smartphone with the experience of using the mobile map performing these calculations remaining relatively painless for the user. This means in the future we are likely to see complex 3D animations and visualizations incorporated into mobile maps. It also could mean that we will experience an increase in both using and creating multimedia information within the mobile map as the barrier to viewing and processing this information decreases.

RQ 1b: In what ways is cartographic design enabled by the hardware of the mobile medium?

Cartographic design possibilities have been greatly extended through mobile mapping. Smartphones in 2017 now have access to on average five unique sensors that extend the mobility of the smartphone and the utility and potentials of the mobile map. To date, mobile map designers are not fully taking advantage of these sensors but as the technology evolves and becomes cheaper in the future, it will be possible to design mobile maps intended to take advantage of sensors such as barometers and advanced Bluetooth receivers to enhance indoor usage accuracy.

Smartphones also are unique in their ability to take advantage of speaker and haptic feedback mechanisms contained within the smartphone. Of the sampled mobile maps in Chapter 3, haptic feedback is still an area underutilized in mobile map design and the unique design potentials made available through this feedback mechanism should be explored further. Sound was more commonly employed for smartphone interactivity, and the use of auditory cues for mobile mapping remains an area to be explored further as all smartphones come equipped with a speaker as well as a microphone.

4.1.2 RQ 2: What are the emerging best practices for mobile map design and development?

RQ 2a: What information is included in the mobile map?

Mobile maps utilize a combination of three types of information in order to add utility for the user: GIS data, sensor data, and non-spatial data. Within GIS data, point data in the form of POIs most commonly are used in mobile maps. The infrequent use of polygons and lines presents opportunities in thematic mapping for cartographers, as most existing mobile maps on the market focus on reference mapping and positioning.

Mobile maps also utilized a variety of sensor data, most notability GPS. GPS and by extension, the location-based services it enables, creates one of the core functionalities of mobile maps: their location awareness. Mobile maps through GPS can show the user not just what a place looks like, but where the user is in real time. While mobile maps overall are adept at utilizing LBS for performing a variety of tasks, mobile maps underutilize other sensor data. While it was outside the scope of this research to record which apps requested access to these sensors, the extension of mobile map utility by other, less common mobility sensors remains an area of further research and design opportunity. For example, what are unique ways a mobile map might integrate a heart rate monitor into its functionality? Are there applications other than wayfinding that mobile maps might make use of the accelerometer, gravity sensor, and gyroscope?

Mobile maps also make use of non-spatial data in the form of off-map text, multimedia, and temporal events within the map. Across the sampled mobile maps, roughly half took advantage of these three forms of data, with events used slightly less frequently than the others. As processing power increases for smartphones, mobile maps should see greater capabilities for designing for truly immersive experiences by employing seamless multimedia and triggering context-relevant events. These different data types combine to create unique mobile mapping experiences for the user and to extend and challenge understandings of space in a way that a purely visual and geographic representation cannot. These data types also could be combined with the unique interactivity and feedback mechanisms available in mobile phones to further differentiate the experience of using a mobile map.

Despite the unique design potential offered through the mobile map, it is also important for mobile map designers to consider the impact that their designs have on the limited smartphone resources of battery life and data volume. There are numerous ways to reduce the power consumption of a mobile map, such as providing the user the ability to choose a dark basemap, limiting background data usage, being conscious of graphic and data processing requirements and providing the ability to limit or reduce what is needed in the map, and providing the user with alternative interaction modes that do not require using the mobile map screen.

RQ 2b: How is this information represented in the mobile map?

Information in mobile maps can be represented a variety of ways. Within my research, I paid particular attention to map features that depicted the user's location, points of interest, regions of interest, and other users. Further research is needed into map features in the form of "lines of interest" (e.g., transit routes), as these were not coded for and therefore their frequency remains unknown. Of the sampled mobile maps, the location of the user was commonly portrayed within the mobile map, but typically it was represented in only one way: as a blue dot. In the future, map designers should question the purpose of their map and decide for themselves if it is necessary to follow convention here or if their map would benefit from a more personified or unique depiction of the user within the mobile map. Another area map designers can explore further is playing with the most useful scale for the user at a given time. By default, most sampled mobile maps loaded showing both the user and their immediate surroundings at a neighborhood level by default. It is important to consider which default scale is most useful for a particular design context because it provides insight for the users for the intended use of the mobile map. Default scale is a powerful tool for the map designer to immerse the users into a specific geographic scale, context, or story.

Points of interest were by far the most common map feature in the sample. The variety of points depicted in the sampled mobile maps, however, was quite low. Generally, the POIs included in the sampled mobile maps were commercial businesses or depictions of commodities to be bought or sold. There is room in mobile map design to explore both POI design conventions (breaking from the teardrop) and the map features that are worthy of including on a mobile map. There is especially a large amount of space for experimenting with points that do not have addresses or exist in less “official” forms of geographic space.

Regions of interest were less consistently depicted within the sampled mobile maps and were less common overall. This is likely related to the low number of thematic maps included in the sample. When regions were depicted, they tended to be administrative boundaries, leaving room for map designers to explore what it would look like to include other regions, even in reference maps. The question even of what regions would be the most useful to depict in a mobile map remains open.

Finally, because mobile maps are typically intended to be used while online, they come with the ability to share and be social within the map itself. Less than half of the sampled mobile maps depicted the inclusion of other map users, and there was a great amount of variety in how other users were included. The lack of standardization means there is likely a large amount of room for map designers to experiment and create social maps that bring people together outside of the map similar to the ‘raid’ feature in *Pokémon Go* that facilitates trainers meeting in real life.

In addition, the basemap of mobile maps plays a large role in both the look and feel of the map as well as its overall utility. The majority the sampled mobile maps included a road basemap as their default, regardless of the overall intended use of the mobile map. Many of the sampled mobile maps would benefit from a custom basemap, both for branding purposes and as a means of reemphasizing the intended utility of the mobile map. Further, road basemaps tended to be a generally light-colored, increasing the energy needed to display the basemap on the device. Future mobile map design could benefit from experimenting with darker basemaps to preserve battery or from increased contrast to improve the mobile experience of the map.

Much discussion in mobile mapping literature has been dedicated to egocentric map views and the influence of a ‘user forward’ map view on map reading skills opposed to having a north orientation. Most of the sampled mobile maps maintained the convention of keeping a north-upwards orientation that users can then adjust using the rotate interaction operator. Often, this adjustment included the ability to reproject the mobile map into a 3D view even if this mode furthered the goal of the map. Likely a hold over from the default map options available in the Google Maps SDK, map designers should think critically about constraining functionality on mobile maps to respect the users' available computing resources.

Sampled mobile maps trended towards taking up a significant portion of the screen with the sampled apps, and often the layout of the map did not change when rotated. The lack of being able to rotate the mobile map is an area of further exploration map designers can tap into. Because smartphones are handheld, there is often very little need for the top of the smartphone to be the top of the design.

RQ 2c: How are users able to interact with these mobile map representations?

Finally, I examined the extent to which users can interact with mobile maps. There were three primary ways that users were able to interact with mobile maps: through changing the viewpoint, through changing what and how data is displayed in the map, and changing the layout of the map. It was very common for users to have the ability to change the viewpoint of the map through a combination of *pan*, *zoom*, and *rotate*. Because these interaction operators often were unconstrained, their widespread scope often made it possible for the user to getting lost in the map, navigating far away from their current location. It was common for mobile map users to *reproject* the map into a 3D view, often without it directly supporting the map's purpose.

Less common was the ability for the user to change or add data to the map. Most maps sampled allowed users to *retrieve* further details about the information in the map, but less frequently filter or search this information, add information in the form of overlays, or to perform calculations within the map. Map designers are underutilizing the power of overlay to add additional information and context in the map, with few maps providing data overlays for users to add.

Surprisingly, about half of the maps allowed the user to adjust the layout of the mobile map. The primary means for adjusting the mobile map layout was sequencing a series of maps in an animation. It was not possible for the user to change how data was displayed in the map in any of the maps sampled. Map designers could take further example of the resymbolize feature, especially for data rendered on the phone. Providing the user with the ability to change the way data is visualized in the map could be useful for those with color blindness or help create more legible maps in bright light.

4.2 Limitations

This work is limited by its inability to draw a direct correlation between the state of the most popular smartphones and the most popular mobile maps because of the amount of time that has passed between data collection for Chapter 2 and Chapter 3. The analysis of most popular smartphones in Chapter 2 was derived from 2017 specifications and the most popular mobile maps were collected in 2019. In the future it would be beneficial to expand the initial sample of smartphones to include 2018 and 2019.

This research ignores the design of smartphones for people with disabilities and the ways that mobile maps can accommodate people with differing abilities. I discussed accessibility issues where easily identified, such as in the case of red-green scaled weather maps. This research, however, predominantly reflects the ability to read and use a mobile map as an able-bodied person.

All of the sampled mobile maps were free. Free apps tend to make money through advertising and through collecting and selling user data. The over-representation of POIs in the sampled apps can be explained as advertisements. The easiest ways for businesses to advertise and therefore for the mobile map to make money is through highlighting businesses within mobile maps. Maps with alternative revenue streams were not tested. An area to be explored in the future would be to include paid maps and compare the two categories, with the understanding that paid mobile maps might have a greater incentive towards careful design and breaking emerging mobile map convention since their users have already committed to the app through payment.

Another issue of cost, all sampled mobile maps were tested on a single Google Pixel Android phone. Therefore, Google defaults and basemaps might have appeared in the sample at much higher rates than they would for other users because the smartphone is designed to use Google basemaps by default. In the future, it would be beneficial to test all sampled mobile maps on an iOS device as well to capture the differences between Android and iOS designs and interaction possibilities.

This research is also limited by the geography and my location as the researcher. I collected and coded data for Chapter 3 entirely in San Francisco, a major U.S. city that in many ways is the testing ground for the Silicon Valley companies that develop many of the mobile maps sampled. Because of my physical location, I was testing these devices in their most ideal conditions, with many of the mobile map developers likely even residing in my neighborhood! Because I was experiencing these apps under idealized conditions, places where the apps breakdown outside of urban environments were not explored and remain unknown. In some cases I was even able to test apps that were limited by geographic area because the San Francisco Bay Area is often included in early access programs, such as was the case with *Citizen*, which was only available in 5 U.S. cities at the time that it was included in the sample.

Finally, the sample of mobile maps was small and therefore the conclusions drawn about the current state of mobile map design could be easily swayed by the inclusion of a few more maps. For example, the sample of mobile maps was largely absent of thematic maps. A larger sample of mobile maps would be able to speak more to if thematic maps are rare within mobile maps generally, or if reference maps are simply the more popular map but thematic maps are still being made.

4.3 Recommendations

Table 4.1 summarizes recommendations and considerations for the future design and development of mobile maps. As mobile maps become increasingly widespread and pervasive in society, mobile cartographers should strive to take full advantage of the smartphone medium.

Table 4.1: Mobile map design and development recommendations

Design & Development Components	Sub-component	Recommendation
Data Characteristics	*GIS Data*	Include other data types such as lines, polygons, and rasters to create a richer and more complex mobile map.
	Sensor Data	Utilize locational sensors other than GPS. These sensors are common enough that user access can be assumed.
	Data Reduction	Utilize locational sensors such as the gyroscope to allow users to dynamically control data and screen usage (e.g., Pokémon Go).
	Offline Mode	Provide users the ability to cache locations, data, and map views to use when they have infrequent access to GPS and mobile data.
Representation Design	*Map Features*	Customize the representation of user location for the overall purpose of the mobile map.
		Consider symbolizing POIs using icons other than teardrop icons, especially if the POI is not a business.
		Consider adding non-administrative ROI information to your mobile map to create a richer mobile map.
		If depicting other users in the mobile map, take care to avoid sharing identifying information in real-time unless users explicitly opt in to this feature.
	Basemaps	Customize basemaps to the overall purpose of the mobile to enhance user outcomes.
		Provide users with high contrast basemap options for use in bright environments.
		Provide users both a dark mode and a light mode to aid in battery conservation.
	Map Views	If the map data covers a large area, consider loading the mobile map centered on the data and not the user for better understanding of the overall functionality of the map.
		Do not provide users with the option to reproject into a 3D view unless it serves an explicit purpose.
		Providing the user with the ability to change the layout on rotation to increase utility while in motion.
	Map Elements	Provide indications of orientation in instances where users can adjust the view of the map from north-up.
		Provide a scale to help users understand distance, especially when in unfamiliar locations.
		Include a legend, especially when mapping ordinal or numeric data.
Interaction Design	*Work Operators*	Utilize overlay to increase the functionality and content options of the mobile map instead of requiring users to filter or search for insight.
		Be intentional about the use of search vs. filter.
		If the mobile map is mean to be used in a constrained geographic area, consider providing a locator map and linking it to the main map for additional user context.
		Consider allowing users to resymbolize data in order to increase utility and understanding of the data in the mobile map, especially for those users with color deficiencies.
	Enabling Operators	When the user shares part of a mobile map, include a representation of the map view in the shared link.
		Allow users to save searches and filters for later use.
		If users can add data to a mobile map, make sure there is an equally transparent way to remove that data.
	Unique Interactivity	If using sound or vibration to accompany map events, allow users to turn these notifications off within the mobile map.
		Question if there are aspects of the mobile map that can be achieved using non-visual feedback.

4.4 Next Steps

The realm of mobile maps is rapidly growing. As mobile maps become more and more pervasive, practitioners and researchers need to understand design conventions in mobile maps as well as their relationship to user expectations, engagement, and usability. I recommend user studies to better understand these intersections.

Augment Reality (AR) in mapping is another rich research area for mobile mapping. AR through smartphones presents unique opportunities to engage and immerse mobile map users. Google maps has recently introduced an AR mode, where the user can have arrows projected onto buildings in the app, using the smartphone camera. This has potentials for immersivity in mobile mapping, and the use of cameras in mapping is an area to be explored further. The presence of multiple cameras in a smartphone is a unique enablement not explored in this research due to its perceived infrequency of use, but the relationship between multimedia information such as photo and video remains an area to be explored further.

Lastly, it would be important to expand the definition of mobile mapping devices to include smartwatches and other wearable sensors that both extend the utility of the smartphone, but also operate as independent mobile mapping devices. Indoor mapping and the potential provided by advanced Bluetooth technology coupled with the promised small network nodes for 5G connectivity.

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APPENDIX A:

App Name	Non-Functional				Data							
					GIS Data			Sensor Data				
	Category	Cost	Release Date	Version	Points	Lines	Polygons	GPS	Positioning	Geographic Search	Other Sensors	Routing Service
Wizards Unite	Adventure	Free	6/29/2019	2.0.2	1	0	0	1	1	0	1	0
Pokémon Go	Adventure	Free	6/28/2019	0.147.1	1	0	0	1	1	0	1	1
PlantNet	Education	Free	5/7/2019	3.0.1	1	0	0	0	0	0	0	0
PlantSnap	Education	Free	7/3/2019	2.02.02	1	0	0	1	1	0	0	0
Stubhub	Events	Free	6/20/2019	7.10.1	1	0	1	1	0	1	0	0
Gametime	Events	Free	5/8/2019	11.2.16	1	0	0	1	0	1	0	0
Capital One	Finance	Free	6/27/2019	5.53.1	1	0	0	1	1	1	0	0
Bank of America	Finance	Free	6/18/2019		1	0	0	1	1	1	0	0
Zomato	Food & Drink	Free	6/20/2019	13.3.6	1	0	0	0	1	1	1	0
Starbucks	Food & Drink	Free	6/19/2019	5.8	1	1	0	1	1	1	0	1
Samsung Health	Health & Fitness	Free	6/14/2019	6.4.0.047	1	1	0	1	1	0	0	0
AllTrails	Health & Fitness	Free	6/28/2019	10.1.2	1	1	0	1	1	1	0	1
Trulia	House & Home	Free	7/2/2019	8.0.0	1	0	1	1	1	1	0	0
Zillow	House & Home	Free	7/3/2019	10.5.426.9091	1	0	1	1	1	1	0	0
Life360	Lifestyle	Free	6/28/2019	19.0.0	1	0	0	1	1	0	1	0
happn	Lifestyle	Free	6/19/2019	24.6.3	1	0	0	1	0	0	0	0
Uber	Maps & Navigation	Free	6/20/2019	4.267.10003	1	1	0	1	1	1	0	1
Waze	Maps & Navigation	Free	6/17/2019	4.52.2.2	1	1	0	1	1	1	0	1
ParkMobile	Maps & Navigation	Free	6/28/2019	7.8.1	1	1	0	1	1	1	0	0
Lyft	Maps & Navigation	Free	7/10/2019	5.87.3.1562155640	1	1	0	1	1	1	1	1
Weedmaps	Medical	Free	7/1/2019	7.60.1	1	0	0	1	1	0	0	0
Leafly	Medical	Free	5/16/2019	7.0.1	1	0	0	1	1	1	0	0
Citizen	News & Magazines	Free	7/5/2019	0.944.0	1	0	1	1	1	1	0	0
Find My Kids	Parenting	Free	7/5/2019	1.9.9	1	0	0	1	1	0	1	0
Groupon	Shopping	Free	6/20/2019	19.8.187388	1	0	0	1	1	1	0	0
OfferUp	Shopping	Free	7/1/2019	3.25.0	0	0	1	1	1	1	0	0
Facebook	Social	Free	6/18/2019	226.0.0.49.120	1	0	0	0	1	1	0	0
Snapchat	Social	Free	6/18/2019	10.59.5.0	1	0	1	1	1	1	0	0
onX Hunt	Sports	Free	6/28/2019	19.24.1	1	1	1	1	1	1	0	0
Fishbrain	Sports	Free	7/5/2019	8	1	0	0	1	1	1	0	0
Google Street View	Travel & Local	Free	6/24/2019	2.0.0.252821521	1	1	1	1	1	1	0	0
Booking	Travel & Local	Free	6/28/2019	18.1	1	0	0	0	0	1	0	0
Google Earth	Travel & Local	Free	7/2/2019	9.2.47.7	1	1	1	1	1	1	0	0
Google Maps	Travel & Local	Free	6/26/2019	10.19.1	1	1	1	1	1	1	1	1
The Weather Channel	Weather	Free	6/25/2019	9.8.1	0	0	1	1	0	1	1	0
AccuWeather	Weather	Free	6/28/2019	6.0.3-free	1	0	1	1	1	1	0	0

App Name	Data								Representation				
	Sensor Data			Non-Spatial Data			Data Conservation		Map Features				Basemaps
	Geocoding Service	Proximity Filter	Reverse Geocoding	Text Results	Multimedia Information	Events	Data Reduction	Offline Mode	Users Location	Points of Interest	Regions of Interest	Other Users	Default Basemap
Wizards Unite	0	0	0	0	1	1	0	0	1	1	0	0	Other
Pokémon Go	0	1	0	0	1	1	1	0	1	1	0	1	Other
PlantNet	0	0	0	0	0	0	0	0	0	1	0	0	Roads
PlantSnap	0	0	0	0	0	0	0	0	1	1	0	0	Roads
Stubhub	0	1	0	1	1	0	0	0	0	1	0	0	Roads
Gametime	0	1	0	1	1	0	0	0	0	1	1	0	Other
Capital One	0	1	0	1	0	0	0	0	1	1	0	0	Roads
Bank of America	0	1	0	1	0	0	0	0	1	1	0	0	Roads
Zomato	0	1	0	1	1	0	0	0	1	1	1	1	Roads
Starbucks	0	1	0	1	0	0	0	0	1	1	0	0	Roads
Samsung Health	0	0	0	0	0	1	0	0	1	0	0	0	Roads
AllTrails	0	1	0	1	0	1	0	1	1	1	0	1	Terrain
Trulia	0	1	0	1	0	0	0	0	1	1	1	0	Roads
Zillow	0	1	0	0	1	0	0	0	1	1	1	0	Roads
Life360	0	0	0	0	1	1	0	0	1	1	0	1	Roads
happn	0	1	0	0	1	0	0	0	0	1	1	1	Roads
Uber	1	0	1	1	0	1	0	0	1	1	0	1	Roads
Waze	1	1	1	1	0	1	1	1	1	1	0	1	Roads
ParkMobile	0	1	0	0	0	0	0	0	1	1	0	0	Roads
Lyft	1	1	1	1	0	1	0	0	1	0	0	1	Roads
Weedmaps	0	1	0	1	1	0	0	0	1	1	0	0	Roads
Leafly	0	1	0	1	1	0	0	0	1	1	0	0	Roads
Citizen	0	1	0	1	1	1	0	0	1	1	1	1	Roads
Find My Kids	0	0	0	0	1	1	0	0	0	1	0	1	Roads
Groupon	0	1	0	1	1	0	0	0	1	1	0	0	Roads
OfferUp	0	1	0	1	0	0	0	0	1	0	1	0	Roads
Facebook	0	1	0	1	1	0	0	0	1	1	0	1	Roads
Snapchat	0	1	0	1	1	1	0	0	1	0	1	1	Roads
onX Hunt	1	0	1	0	0	1	0	1	1	1	1	0	Roads
Fishbrain	0	1	0	1	1	0	0	0	1	1	0	1	Terrain
Google Street View	0	1	0	1	1	0	0	0	1	1	1	1	Roads
Booking	0	1	0	1	1	0	0	0	0	1	0	0	Roads
Google Earth	1	1	1	1	1	0	1	1	1	1	1	1	Satellite
Google Maps	1	1	1	1	1	1	0	1	1	1	1	1	Roads
The Weather Channel	0	0	0	0	0	0	0	0	1	0	0	0	Roads
AccuWeather	0	0	0	0	1	0	0	0	1	0	0	0	Roads

App Name	Representation						
	Basemaps		Map Views				
	Basemap Colors - Dark Mode	Basemap Colors - Light Mode	Default Orientation - North	Default Orientation - User Forward	Default Loading View - Egocentric	Dimensioniality - 2D	Dimensioniality - 3D
Wizards Unite	1	0	0	1	1	0	1
Pokémon Go	0	1	0	1	1	0	1
PlantNet	0	1	1	0	0	1	1
PlantSnap	0	1	1	0	1	1	1
Stubhub	0	1	1	0	1	1	0
Gametime	0	1	0	1	0	1	0
Capital One	0	1	1	0	1	1	0
Bank of America	0	1	1	0	1	1	1
Zomato	0	1	1	0	0	1	0
Starbucks	0	1	1	0	1	1	0
Samsung Health	0	1	1	0	1	1	1
AllTrails	0	1	1	0	0	1	0
Trulia	0	1	1	0	0	1	1
Zillow	0	1	1	0	0	1	1
Life360	0	1	1	0	0	1	1
happn	0	1	1	0	0	1	0
Uber	0	1	1	0	1	1	0
Waze	1	1	1	0	1	1	1
ParkMobile	0	1	1	0	1	1	1
Lyft	0	1	1	0	1	1	0
Weedmaps	0	1	1	0	1	1	1
Leafly	0	1	1	0	1	1	0
Citizen	1	0	1	0	1	1	0
Find My Kids	0	1	1	0	1	1	0
Groupon	0	1	1	0	0	1	0
OfferUp	0	1	1	0	0	1	1
Facebook	0	1	1	0	1	1	0
Snapchat	0	1	1	0	1	1	0
onX Hunt	1	1	1	0	1	1	0
Fishbrain	1	1	1	0	1	1	0
Google Street View	0	1	1	0	1	1	1
Booking	0	1	1	0	0	1	1
Google Earth	1	0	1	0	0	1	1
Google Maps	1	1	1	0	1	1	1
The Weather Channel	1	1	1	0	0	1	0
AccuWeather	1	1	1	0	1	1	1

App Name	Representation							Interaction			
	Map Views				Map Elements			Work Operators			
	Map Size	Change on Rotation	Default Scale	Projection - Web Mercator	Orientation Symbology	Scale	Legend	Pan	Zoom	Zoom - Information Complexity Adjustment	Rotate
Wizards Unite	5	0	Neighborhood	0	1	0	0	0	1	0	1
Pokémon Go	5	0	Neighborhood	0	1	0	0	0	1	0	1
PlantNet	5	0	Regional	1	1	0	0	1	1	1	1
PlantSnap	5	0	Neighborhood	1	0	0	0	1	1	1	1
Stubhub	2	0	Regional	1	0	0	0	1	1	1	0
Gametime	4	0	Other: Stadium	0	0	0	0	1	1	0	0
Capital One	5	1	Neighborhood	1	0	0	0	1	1	1	1
Bank of America	4	0	Neighborhood	1	0	0	0	1	1	1	1
Zomato	2	0	Neighborhood	1	0	0	0	1	1	1	0
Starbucks	2	0	City	1	0	0	0	1	1	1	0
Samsung Health	3	0	Neighborhood	1	1	0	0	0	1	1	1
AllTrails	3	1	Country	1	0	1	0	1	1	1	1
Trulia	5	0	Neighborhood	1	0	0	1	1	1	1	1
Zillow	4	1	City	1	0	0	0	1	1	1	1
Life360	4	0	Neighborhood	1	0	0	0	1	1	1	1
happn	5	0	Neighborhood	1	0	0	0	1	1	1	0
Uber	3	0	Neighborhood	1	0	0	0	1	1	1	0
Waze	5	1	Neighborhood	1	0	0	0	1	1	1	1
ParkMobile	5	0	Neighborhood	1	1	0	0	1	1	1	1
Lyft	3	0	Neighborhood	1	0	0	0	1	1	1	0
Weedmaps	5	0	City	1	0	0	0	1	1	1	1
Leafly	4	0	City	1	0	0	0	1	1	1	0
Citizen	3	0	Regional	1	1	0	1	1	1	1	1
Find My Kids	5	0	Neighborhood	1	0	0	0	1	1	1	0
Groupon	4	1	City	1	0	0	0	1	1	1	1
OfferUp	5	0	Neighborhood	1	0	0	0	1	1	1	1
Facebook	1	0	Neighborhood	1	0	0	0	1	1	1	1
Snapchat	5	0	Neighborhood	1	0	0	0	1	1	1	0
onX Hunt	5	0	City	1	1	1	0	1	1	1	1
Fishbrain	4	0	City	1	1	0	1	1	1	1	0
Google Street View	3	1	Country	1	0	0	0	1	1	1	0
Booking	5	0	Neighborhood	1	1	1	0	1	1	1	1
Google Earth	5	1	Global	0	1	0	0	1	1	1	1
Google Maps	4	1	Neighborhood	1	1	1	0	1	1	1	1
The Weather Channel	4	0	Regional	1	0	0	1	1	1	1	0
AccuWeather	5	0	Regional	1	0	0	1	1	1	1	0

App Name	Interaction												
	Work Operators												
	Overlay	Overlay - Bicycling	Overlay - Transit	Underlay - Roads	Underlay - Satellite	Underlay - Terrain	Filter	Search	Calculate	Retrieve	Arrange	Sequence	Reproject
Wizards Unite	0	0	0	0	0	0	0	0	0	1	1	0	1
Pokémon Go	0	0	0	0	0	0	0	0	0	1	1	0	1
PlantNet	0	0	0	1	0	0	0	0	0	1	0	0	1
PlantSnap	0	0	0	1	0	0	0	0	0	1	0	0	1
Stubhub	0	0	0	1	0	0	0	0	0	1	1	0	0
Gametime	0	0	0	0	0	0	1	1	0	1	1	0	0
Capital One	0	0	0	1	0	0	1	1	0	1	0	0	0
Bank of America	0	0	0	1	0	0	1	1	0	1	0	0	1
Zomato	0	0	0	1	0	0	1	1	0	1	1	0	0
Starbucks	0	0	0	1	0	0	1	1	1	1	1	0	0
Samsung Health	1	0	0	1	1	1	0	0	0	0	1	0	1
AllTrails	1	0	0	1	1	1	1	1	0	1	1	1	0
Trulia	1	0	0	1	1	0	1	1	0	1	1	0	1
Zillow	1	0	0	1	1	0	1	1	0	1	0	0	1
Life360	1	0	0	1	1	0	1	0	1	1	1	1	1
happn	0	0	0	1	0	0	0	0	0	1	0	0	0
Uber	1	0	0	1	0	0	0	1	1	1	0	0	0
Waze	1	0	0	1	0	0	1	1	1	1	1	0	0
ParkMobile	1	0	0	1	1	0	1	1	0	1	0	0	1
Lyft	1	0	0	1	0	0	0	1	1	1	1	0	0
Weedmaps	0	0	0	1	0	0	1	1	0	1	1	0	1
Leafly	0	0	0	1	0	0	1	1	0	1	0	0	0
Citizen	0	0	0	1	0	0	0	1	0	1	0	0	0
Find My Kids	1	0	0	1	1	0	0	0	0	1	0	0	0
Groupon	0	0	0	1	0	0	1	1	0	1	0	0	0
OfferUp	0	0	0	1	0	0	0	0	0	0	0	0	1
Facebook	0	0	0	1	0	0	1	1	0	1	1	0	0
Snapchat	1	0	0	1	1	1	0	1	0	1	0	0	0
onX Hunt	1	0	0	0	1	1	0	1	1	1	1	0	0
Fishbrain	1	0	0	0	1	1	0	1	0	1	1	0	0
Google Street View	1	0	0	1	1	0	0	1	0	1	1	0	1
Booking	0	0	0	1	1	1	1	1	0	1	0	0	1
Google Earth	1	0	0	0	1	0	1	1	1	1	1	1	1
Google Maps	1	1	1	1	1	1	1	1	1	1	1	1	1
The Weather Channel	1	0	0	1	1	0	0	1	0	1	0	1	0
AccuWeather	1	0	0	1	0	0	0	1	0	1	0	1	1

App Name	Interaction										
	Work Operators		Enabling Operators					Unique Interactivity			
	Reexpress	Resymbolize	Import	Export - Share	Save	Edit	Annotate	Haptic Feedback	Sound - Language Prompts	Sound - Non-Language Prompts	
Wizards Unite	0	0	0	0	0	0	0	1	1	1	
Pokémon Go	0	0	0	0	0	0	0	1	0	1	
PlantNet	0	0	0	0	0	1	0	0	0	0	
PlantSnap	0	0	0	1	0	1	0	0	0	0	
Stubhub	0	0	0	1	0	0	0	0	0	0	
Gametime	0	0	0	1	0	0	0	0	0	0	
Capital One	0	0	0	0	0	0	0	0	0	0	
Bank of America	0	0	0	0	0	0	0	0	0	0	
Zomato	0	0	0	1	1	0	1	0	0	0	
Starbucks	0	0	0	0	0	0	0	0	0	0	
Samsung Health	0	0	0	1	1	0	0	0	1	0	
AllTrails	0	0	1	1	1	0	1	0	0	0	
Trulia	0	0	0	1	1	0	1	0	0	0	
Zillow	0	0	0	1	1	0	1	0	0	0	
Life360	0	0	0	1	0	1	1	0	0	1	
happn	0	0	0	0	0	0	0	0	0	0	
Uber	0	0	0	1	0	0	0	1	0	1	
Waze	0	1	0	1	1	1	1	1	1	1	
ParkMobile	0	0	0	0	0	0	0	0	0	0	
Lyft	0	0	0	1	0	0	0	1	0	1	
Weedmaps	0	0	0	1	0	0	0	0	0	0	
Leafly	0	0	0	1	0	0	0	0	0	0	
Citizen	0	0	0	1	0	0	1	0	0	0	
Find My Kids	0	0	0	1	0	0	1	0	1	1	
Groupon	0	0	0	1	0	0	0	0	0	0	
OfferUp	0	0	0	1	0	0	0	0	0	0	
Facebook	0	0	0	1	0	0	0	0	0	0	
Snapchat	0	0	0	1	0	0	0	0	0	0	
onX Hunt	0	0	1	1	1	1	1	0	0	0	
Fishbrain	0	0	0	1	0	1	1	0	0	0	
Google Street View	0	0	0	1	0	1	0	0	0	0	
Booking	0	0	0	1	1	0	0	0	0	0	
Google Earth	0	0	1	1	1	1	1	0	0	0	
Google Maps	0	0	0	1	1	1	1	1	1	1	
The Weather Channel	0	0	0	0	0	0	0	0	0	0	
AccuWeather	0	0	0	1	0	0	0	0	0	0	